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MASTER

Contactfree, high accuracy and high speed system for positioning filaments : an electromagnetical actuator

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EINDHOVEN UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
Measurement and Control Section

CONTACTFREE, HIGH ACCURACY AND HIGH SPEED SYSTEM FOR POSITIONING FILAMENTS

an electromagnetical actuator

by : ing. H.W. Lentjes

carried out from may 1992 to december 1992
at Philips Lighting Eindhoven
department Advanced Industrial Technologies

commissioned by prof. dr. ir. A.C. Backx
under supervision of dr. ir. A.A.H. Damen
date : 9 december 1992

Lentjes, H.W.; Contactfree, high accuracy and high speed system for positioning filaments

M.Sc. Thesis, Measurement and Control Section ER,
Electrical Engineering, Eindhoven University of Technology,
The Netherlands, December 1992.

Due to the fact that the new generations of lamps are being miniaturised the mechanical positioning systems are becoming more and more expensive. Also it is getting more and more difficult for having a physical contact between the positioning actuator and the filament, which increases the problems of positioning. In this study a high speed and high accuracy contactless positioning system has been developed by means of a magnetic coil.

In this report the derivation of the static force-position model of the electro magnetic actuator is being described. Furthermore the implementation of the controller is being discussed together with the practical setup and the mechanical parts and sizes that are needed to implement a contactless positioning system in an industrial environment.

In the appendices some measurement results can be found and also the complete derivation of the electro magnetic actuator model.

The most important conclusions are that it proved to be possible to design a system which enables a high accuracy combined with a high speed. Further it showed that the system designed has a competitive price tag if it is compared with mechanical positioning systems that even don't have nearly the same accuracy nor the same speed. The speed that could be achieved is, including the insertion of the filament into the quartztube, 0.4 seconds per positioning cycle. Furthermore the achieved accuracy is 20 μm which is the accuracy of the used sensor.

These conclusions could mean that future positioning systems could be implemented as contactfree versions. Also, because the system is cheaper and easier to maintain, the costs per lamp could become less which results in higher profits.

Contents

Content (continued)

The used symbols and their meaning

x : the position
Δx : the difference between two positions
B : the magnetical induction
H : the magnetical field intensity
μ : the magnetical permeability
μ_o : the magnetical permeability of air
μ_r : the relative permeability
l : the length of the coil
N : the number of turns
I : the current through the coil
A : the area of the nickelstrip
F_m : the force due to the magnetical field
F_g : the force due to the gravitation
m : the mass of the nickelstrip and the filament together
g : the gravitation acceleration
T : tesla
$\underline{u}_x$: unity vector in x direction

Introduction

This M. Sc. project has been carried out to design a new method to position filaments without any physical contact.

Why should the positioning be contactfree? The size of the quartztube in which the filament is placed, see the figures below, is being decreased more and more. This, however, results in problems during the positioning. Due to the small size and the fact that the filament is completely inside the quartztube makes it almost impossible to position mechanically while holding the filament. Furthermore the desired accuracy has been increased also which would mean that the mechanical systems would become much more expensive.

Furthermore there is a tendency toward miniaturising which means that the requirements of the accuracy will increase. An increased accuracy, however, will also result in much more expensive mechanical systems. Also this will result in an increased positioning time which should be avoided.

This resulted in the idea of an M.Sc. project where the possibilities should be studied of a contactfree positioning that has to have an increased accuracy, must be at least as fast as existing systems and the priceticket, that accompanies the system, has to be competitive. If this should be possible a controlsystem has to be developed which enables the automatic positioning.

In the figures below the industrial set-up can be seen and the steps needed in order to get a final working product. The first step includes the braking and positioning the filament as designed in this study.

The next step is the melting and closing of the tube at the opposite end, in order that the coil body won't suffer unnecessarily of the heat. During this step the position is stabilised.

This step is followed by the closing of the tube at the other end. This is done after the tube has been removed from the positioning system.

The final step consists of the removal of the nickelstrip which renders the total lamp.

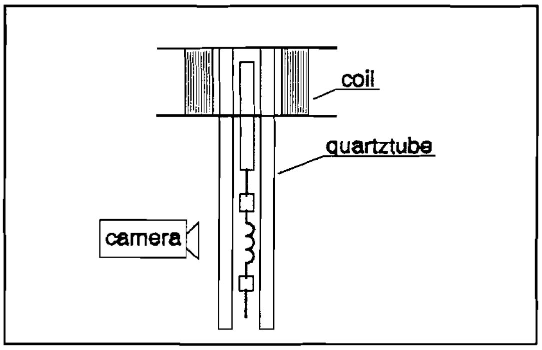
In an industrial set up the camera measures the position of the filament. This position is compared with the desired position and renders the error signal which is being used by the controller. This controller then changes the current in the coil in order to reduce the error by changing the resulting force on the nickelstrip.

The laboratory set up uses a laser sensor to detect the height of the filament. Furthermore, the filament has been replaced by a flag which drives the sensor and whose height is being measured.

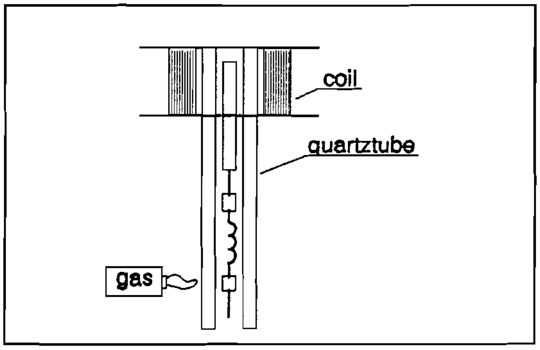
In this report the first chapter consists of a brief description of the new generation of lamps and the topics that are important while developing new types of lamps. The second chapter describes the goals of this project while the next chapter is a description of the sensor.

After a description of the first test results the statical force-height model is being described in the chapters 5 to 9. Combining this with the controller demands of chapter 10 leads to the implementation of the controller as described in chapter 11 and its test results which can be seen in chapter 12.

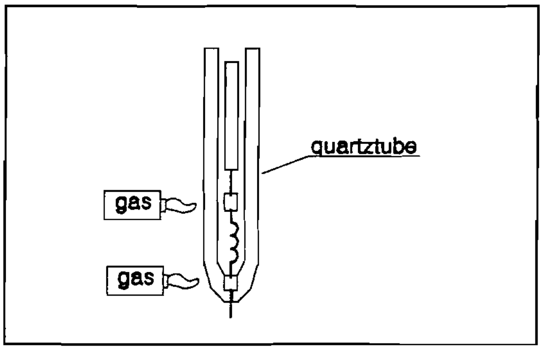
This leads to a totally automated system, see chapter 13, which has some important advantages which can be seen in chapter 14. To implement this in the vertical set up some useful practical tips can be found in chapter 15 while chapter 16 holds some ideas in order to make a horizontal set up.



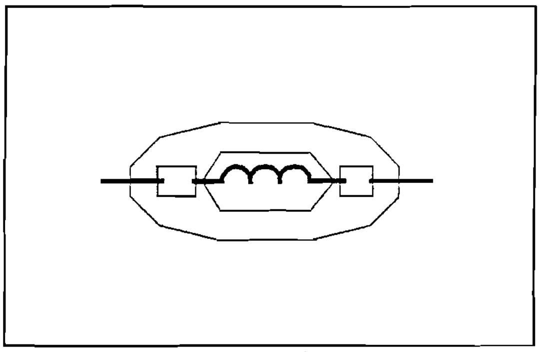
step I : positioning of the filament



step II : melting of the tube at one side



step III : melting on the other side



step IV : the final lamp

1. Some basics about lamps

The older and wellknown incandescent lamp is being replaced more and more by other types that are having a higher yield of light, a longer and improved lifetime or even a totally different working principle.

The newest lamps that are being made, consist of two major parts:

- a burner
- an optical system

The burner is the element that actually generates the light after which the optical system bundles it into a parallel beam and assures in this way the right direction and the parallelism of the beam. Both elements together are called the lightsystem.

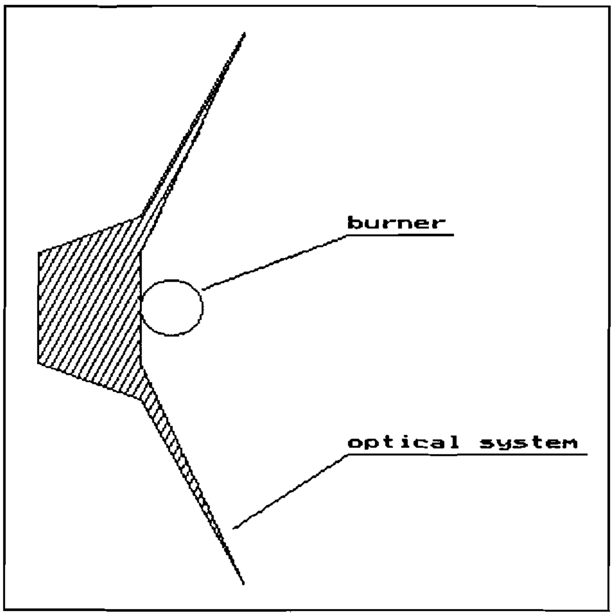


figure 1.1 : the lightsystem

The last years there has started a tendency in miniaturising, and this in the broadest sense of the word. Not only in integrated circuits but also in other technological areas. Even the designers of the new lightbulbs have been infected with those ideas.

Main reason for miniaturising is that it is less expensive to build an optical system for the smaller burners. The reason for this is that a small filament can be represented as a point from which the light is generated. Therefore a simple optical system can be used to generate a parallel beam. Would the beam be generated by a burner that is larger and can't be replaced by a point, then the optical system that will be needed is more complex and thus more expensive to make.

However, during this miniaturising of the burner the position of the filament inside the bulb becomes more and more important. So the miniaturising of the burner results in the need for a high accuracy positioning system. This need has resulted in the M.Sc. Thesis you are now reading.

In the most new developed lamps the glass bulbs are being replaced by quartz. This is done because the temperature of the filament gets higher every generation of lamps. Due to the lower thermal expansion of the quartz there won't be any thermal stresses in the bulb which can be used to increase the pressure inside the bulb.

Furthermore it is possible to heat the quartz, with the intention of melting it, in a place next to the cooling which is needed to assure that the halogen won't vaporize. The bulb can thus be filled with liquid Xenon or Krypton (- 230 ℃) and then be closed by melting the quartz (+ 2500 ℃).

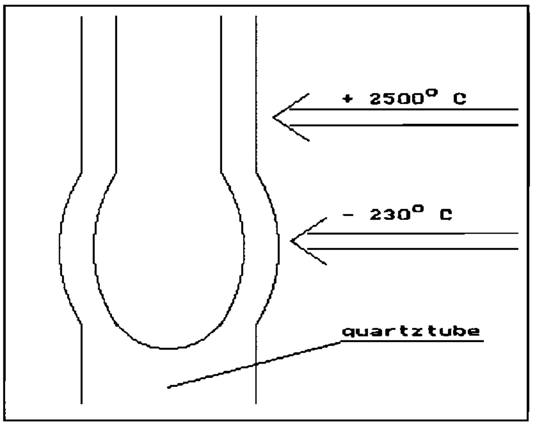


figure 1.2 : the melting

Combining a high temperature with a high filling pressure ensures an improved lifetime of the lamp.

The high temperature results in an increased generation of light in the visible part of the spectrum (see figure 1.3).

In figure 1.3 it can be noticed that the share of the visible light increases when the temperature is increased. But a negative effect is that the UV part is also being increased.

Furthermore the increased temperature results in faster evaporation of the filament, which will become thinner as a result of this. The resistance of the filament will be increased and, as a result of this, the temperature will follow. This effect will shorten the lifetime significantly. Another result is that the evaporated material will form a thin layer on the inside of the bulb which yields in a lower light emission. Both effects will decrease the economic lifetime of the lamp.

To cope with both effects the lamp will be filled under a high pressure with a halogen. Now there won't evaporate as much material as before and the evaporated material will be combined into a chemical substance with the halogen. This substance will move towards the filament were a second chemical reaction causes it to form material,and precipitate onto the filament, and halogen. In this way we have achieved a closed and stable chemical circulation which increases the lifetime of the lamp.

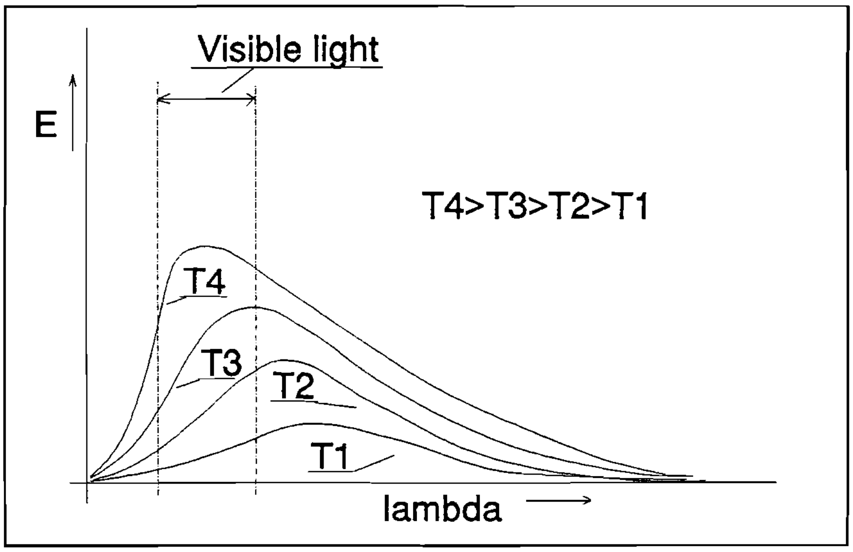


figure 1.3 : the yield of the light as a function of the wavelength

Another reason for choosing quartz rather than glass is for example that glass is too vulnerable in certain surroundings. In gas discharge lamps, as the D1, the surrounding environment is too aggressive for normal glass due to the discharge.

A problem while miniaturising is the decreasing distance between the two poles in the gas discharge lamp. Decreasing the distance has to result in increasing the pressure. The relation between p*d (pressure multiplied by the distance) and the ignition voltage is shown in figure 1.4 and is derived by Paschen. We notice that a small distance combined with a low pressure results in a high ignition voltage because the number of available atoms between the poles is very small. Should, however, the pressure be increased too much then there will be needed much more energy to loosen the electrons from the shell of the atoms and thus generating light emission.

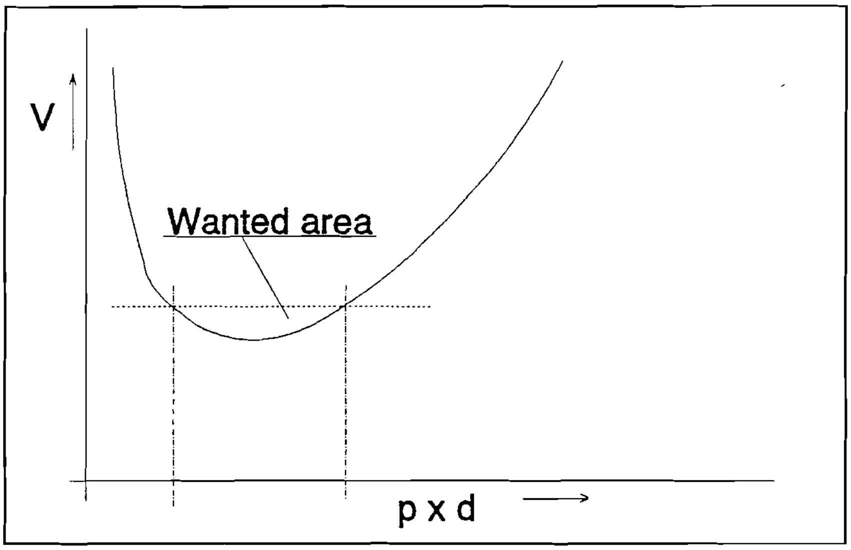


figure 1.4 : the $V_{ignition}$ - p*d relation

To stay in the wanted area we have to decrease the pressure if the distance increases. The increasing distance could result from the burning of the electrodes. A good control of the ignition current is necessary to achieve a long lifetime.

In gas discharge lamps there are two electrodes placed together with some vaporized mercury. By ensuring a current in the gas electrical energy is converted into mechanical energy (the movement of the electrons). This mechanical energy will partially result in light during the collision of an electron with an gasatom. A second part will be lost as a result of the collisions with the bulb. Those losses will be big but can be decreased by filling the bulb with an inert gas. The number of collisions with the bulb will decrease significantly. As a result of the larger excitation and ionisation level of the rare gas, the collisions between electron and a rare gas atom will be elastic. This results in strongly decreased internal losses.

The main problem of a gas discharge lamp is however the ignition. To start the lamp there has to be a spark generated by one or more large voltage pulses across the electrodes. The arcing voltage can be reduced by using special means such as starting aids (ignition coils, antenna, etc.) or by choosing an appropriate gas.

After the lamp has been started it enters the second phase. This phase is called the glow discharge phase which is only possible if the power source can provide enough energy to the electrodes to ensure that they can reach the necessary emission temperature. It is not until now that the electrons can leave the electrode because a high temperature lowers the necessary voltage. However, should the glow discharge phase take to much time it will result in a strongly reduced lifetime of the lamp as a result of the destruction of the electrodes.

To lower the discharge voltage the Penningeffect is being used. This effect can be explained as follows. A filling gas is used based on neon and argon. In the developing glow discharge many neon atoms will be excited by collisions with the electrons resulting in a great deal of metastable neon atoms who could collide with argon atoms. The ionisation level of the argon atoms is lower than the energy level of the metastable neon resulting in argon atoms which are being ionised. In this way a new electron is generated, an important fact for the discharge.

Other means for starting the discharge are:

- an electronical starting device : generates high voltages
- antenna : a conducting antenna is being placed just outside of the discharge bulb. As a result of the capacitive interaction between antenna and the glow discharge the ignition is enhanced.
- extra electrodes : the glow discharge is started between the main electrode and the extra electrode after which it is easier to start a glow discharge between the main electrodes

Furthermore it is important for making a good lamp that sealing of the bulb is of a good quality. This can be achieved by using material with almost the same mechanical properties by which is achieved that there are no stresses in the lamp that has its working temperature.

Thermal stress mostly results in a fractured surface of the glass. To solve this problem a molybdenum strip seal has been used which is very thin and has nearly the same coefficient of expansion as quartz and leads to the familiar band bridge construction (see figure 1.5).

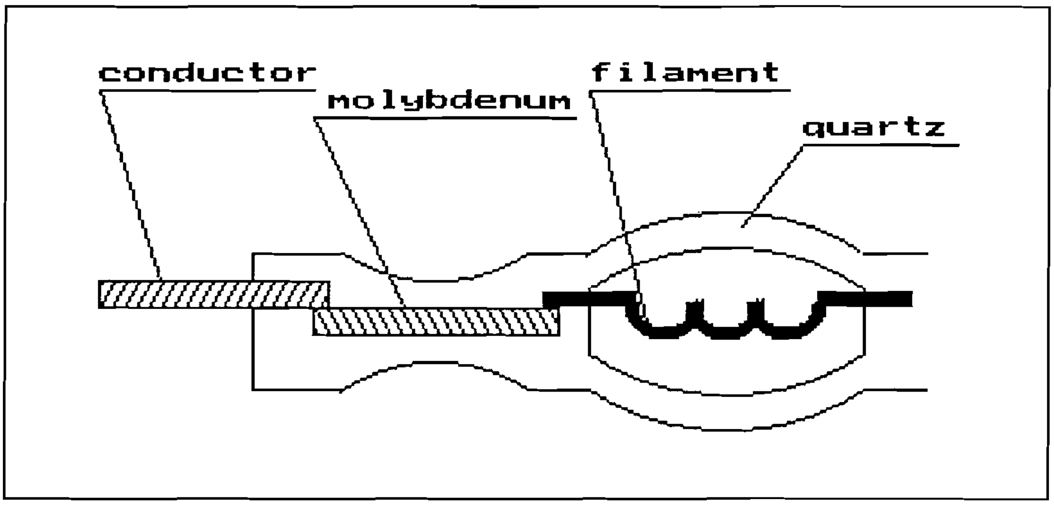


figure 1.5 : the band bridge construction

The efficiency is an important fact in the designing of a good lamp. This is expressed in lumens/watt. The relation is that the efficiency increases with increasing temperature which can be seen in figure 1.3. However an increasing temperature results in a shortened lifetime which is caused by a more rapid evaporation of the filament.

Both effects result in a efficiency - life time function as in figure 1.6.

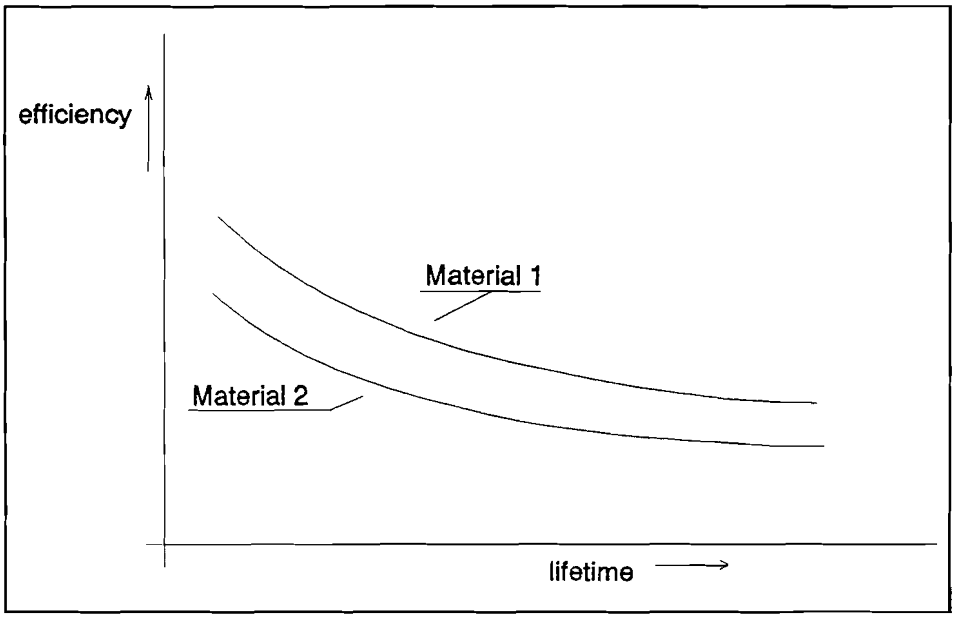


figure 1.6 : efficiency - lifetime function

To the customer the colourtemperature is very important because it determines the colour of the light and everything it shines onto.

The colourtemperature is determined by comparing the lamp with the black body radiation. The intensity-curve as a function of the wavelength at different temperatures can be seen in figure 1.7.

By increasing the temperature the colour of the source will be lighter. The curve is derived by Planck according to the so called Planck's law.

By comparing the intensity-curve of a lamp with the curves of a black radiation body the colourtemperature can be determined as that temperature which has the best fit between the two curves.

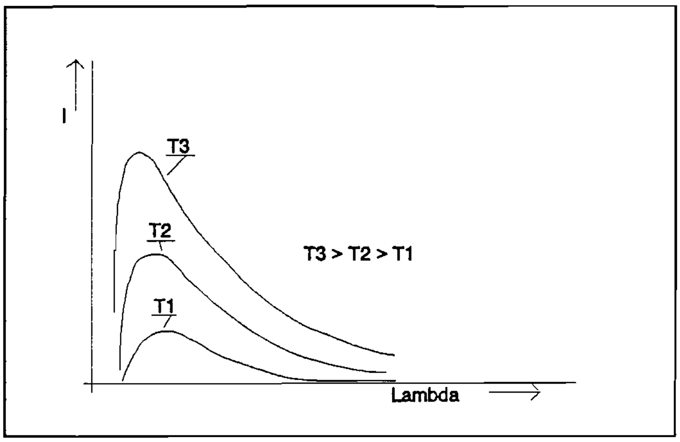


figure 1.7 : the intensity curve as a function of lambda

Another way of determing the colourtemperature is by using the colourtriangle, because each colour can be described as a combination of two values, x and y.

The value of x and y can be calculated by the following method. By choosing three primary colours, for example red (R), green (G) and blue (B) most of the possible colours can be made by a combination (as is happening in a T.V. set). The primary colours R,G and B represent spectralines with a certain intensity which doesn't need to be the same to get the intended colour.

If the object is making a blue-green spectraline (BG) it appears to that it is not possible by using only positive intensity values. The combination needed is BG=B+G, but the colour rendering doesn't match. By adding some red (R) to BG the right colour rendering is achieved. So BG+R=B+G which means adding a negative value for red to B+G.

This phenomena of the negative intensities can be perceived independent of the choice of the primary colours. This should result in the colourtriangle in colours who would be outside the triangle. The CIE has therefore defined imaginary primary colours which means even more blue than normal blue, more green than normal green and more red than normal red.

These primary colours are only used for calculation and don't have any physical meaning and are referred to as X,Y and Z. The value 1 for X,Y and Z defines that the colours represented by X,Y and Z have the same energy.

The calculation of the coordinates in the colourtriangle can be made as is explained in the next steps.

In the first step the ratios are being determined of the contribution of each separate colour to the total.

$$x = \frac{X}{X + Y + Z} \qquad y = \frac{Y}{X + Y + Z} \qquad z = \frac{Z}{X + Y + Z} = 1 - x - y$$

Notice that there is a difference between the capital X,Y and Z and the small x,y and z. The capitals represented the represent the energy ratio of each separate colour while the small letters represent the ratio of a colour into the total colour.

The colours which are being represented by X,Y and Z are imaginary for the same reason as discussed before. If we assume that X,Y and Z represent red, green and blue than a certain colour orange can be represented by 75 percent red, 60 percent green and 15 percent blue. The percentages are a ratio to the 100 percentage which achieves that red, green and blue have the same energy levels. Now the colour orange is represented by X=0.75, Y=0.60 and Z=0.15. Those X,Y and Z values are ratios and don't have any dimension. If now from these X,Y and Z values the x,y and z are being calculated we obtain x=0.5, y=0.4 and z=0.1. It can be noticed that x+y+z=1 as is stated in the formula. If this a-priori knowledge is being used the colour can be represented by a coordinate in the two-dimensional space x-y.

In the next step this coordinate is being placed in the colourtriangle and can be compared with the curve of a black radiation body. The temperature that corresponds the best with the colour is the colourtemperature (see figure 1.8a and 1.8b).

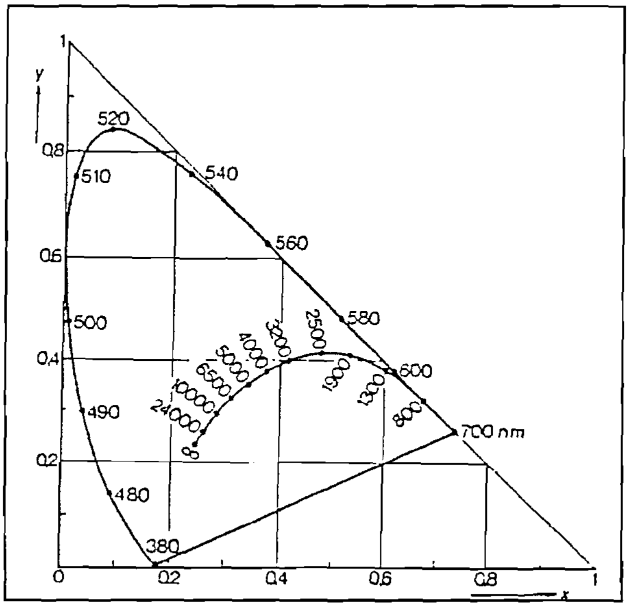


figure 1.8a : the colourtriangle with the curve of a black radiation body

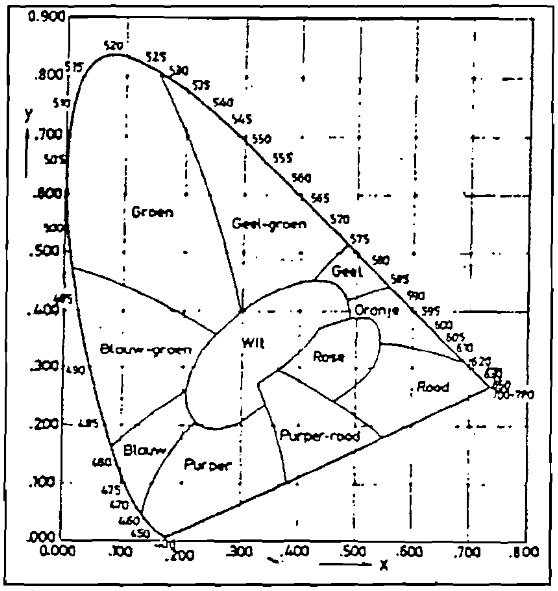


figure 1.8b : the colourdistribution in the colourtriangle

From this it can be concluded that a lamp has a real temperature and a colourtemperature which, usually, aren't the same. For a normal glowing lamp the difference between real temperature and colourtemperature is approximately 50 ℃, but for other lamps this difference can be much larger. A fluorescent lamp for example has a temperature of about 40 ℃ (313 K), whereas the colourtemperature normally is somewhere between 3000 K and 6500 K depending on the used phosphors.

One of the demands that are made to the colourrepresentation is that the objectcolours have to be as if they would be lit by sunlight. However for the testing of natural products like meat, cotton, etc., often one doesn't want it to look natural. In those cases the merchandiser wants it to look better so he buys a lamp with a colourtemperatures which fits to his needs. This is often done with the intention to have a more tastier look of the meat by using lamps who have a great deal of red light.

Researchers have found that lightsources, or a combination of lightsources, who have a spectral distribution which fits the most to that of a black radiation body achieve the most natural look of the objects being lit. These researchers have been looking at hospitals and musea.

From this story it can be concluded that lighting is an area in which there is still a lot of development going on in order to achieve another product with other materials. The developing areas depend on the customers wishes and contain other colourtemperatures, smaller lightsources, prolonged lifetimes, etc.

2. what should be achieved with this project

In the last chapter it became clear that the common tendency to miniaturising is also noticeable in the lighting section. As a result of the miniaturising of the lamps the absolute tolerances become smaller also (for example 100 μm on a 40 mm lamp becomes approximately 10 μm for those smaller ones). The mechanical system used to position the filament will become to expensive and to slow. The smallest step that the machine can make has to be less than the accuracy that is desired so it will become much more expensive.

Another problem is that the total filament is inside the quartztube and as a result of this it can't be held tight during the positioning steps. As a result of this it is not possible to retract a filament that has had an overshoot, which is, by the way, easily to occur. This fact will slow the positioning down because it has to be done in at least two steps: one fast until about 95 percent of the total step has been made followed by a slower and more accurate positioning. The last step is the slowest and will become even slower if the desired accuracy increases.

This has led to the idea of designing a faster, better and, if possible, cheaper way of positioning. The only restriction was, beside of the necessary time, that it had to be done without making any physical contact between the positioning device and the filament.

This restriction meant that it had to be done by means of an electrical or a magnetic field generating thus an electrical or a magnetical force.

An analysis of the objective shows that the positioning should be done in vertical direction. As a result from this the gravity force can be used for pulling the filament down and a force generated by the positioning device ought to move the filament up.

The electrostatical force has a disadvantage that the object, in this case the filament, has to be charged in order to generate the desired force. Furthermore an electrical force is smaller than the equivalent magnetical one. So if we could use the magnetical force it would have advantages above the electrical.

The magnetical force can be generated in two ways:

- a force as a result from a current in a magnetical field
- a force on a magnetical soft material in a magnetical field

The magnetical force can be generated in two ways:

- a magnetical field in the direction of movement (see figure 2.3)
- a magnetical field perpendicular to the direction of movement (see figure 2.2)

A field that is perpendicular to the direction of movement has as disadvantage that there is always a force perpendicular to the direction of movement. Also is the force in the direction of movement smaller than in the situation where the field is in the direction of movement. This is due to the fact that the change of magnetical energy is less than it is in the situation of a field in the direction of movement.

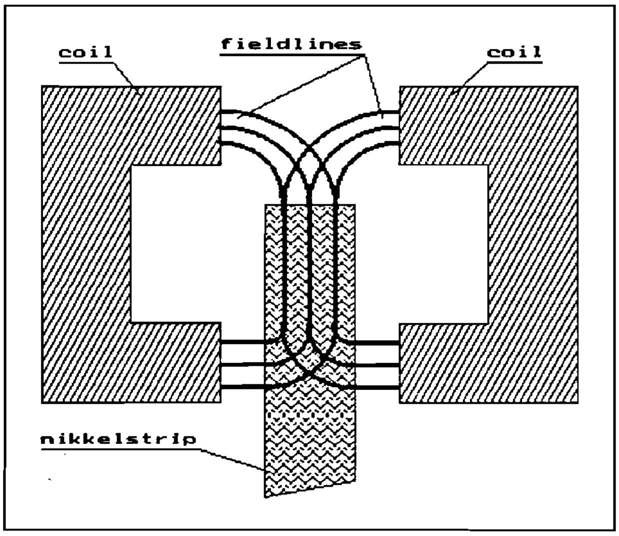


figure 2.2 : the perpendicular field

If a field is chosen in the direction of movement then there is also the possibility of a greater range of movement because the field is from the beginning of the coil until the end, while the field perpendicular to the direction of movement can only be used if the nickelstrip is inbetween the two poles.

The generation of the field that is needed can be done using a coil shown as in figure 2.3.

By controlling the current through the coil the field can be changed and also the force on the nickelstrip. If the gravity force is compensated the filament won't move, but is the current is increased the resulting force will point upwards and the filament will move up. The same will happen for a movement down by decreasing the current the resulting force will get negative and point down which will move the filament down. This mechanism will enable a controlled movement up or down.

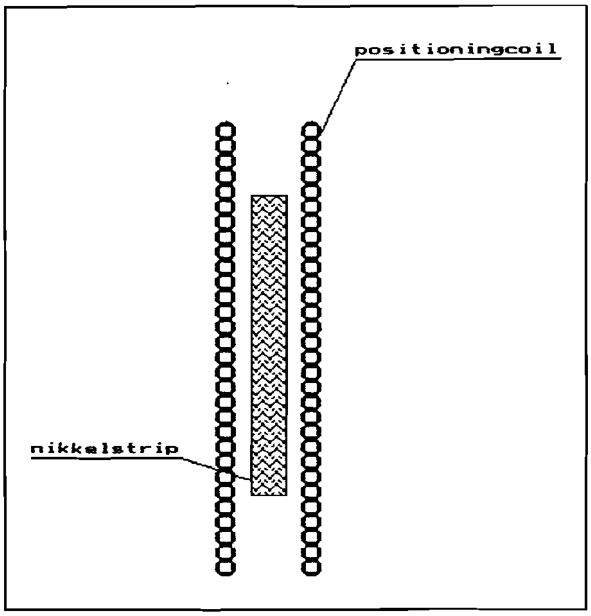


figure 2.3 : coil with nickelstrip

Though the idea using a magnetical field for positioning purposes has been brought up a time ago, there aren't many commercially available applications. This has been partially a result of a lack of enough numerical power for a low price. Most applications are concerning the hovering of a train which is in an order of millimetres and a mass of several tons where on the contrary this concerns a fine positioning system in micrometer area of a mass of less than one gramm.

Because there ain't a real commercially application the outcome of this project may have an influence on other sections of positioning. An application that could be interesting is the positioning of a laserhead in a cd-player. The head will have less disturbances due to the fact that it is contactfree. Therefore the heavy and expensive construction, which is used to damp the mechanical vibration of the motor, could become unnecessary and can be replace by a lighter and cheaper version. A necessarily fact is however that there has to be a good method for measuring the position of the object.

An advantage of a contactfree positioning system is that the accuracy is mainly determined by the measurement accuracy of the sensor.

A disadvantage is that the force is dependent of different factors which could make the system expensive in a mass-production.

This force is depending of:

- the number of windings of the coil
- the current in the coil
- the length of the coil
- the magnetical properties of the moving object
- the useful area of the moving object
- the position of the nickelstrip

The result of the last two factors are that a controller has to take this in account by means of robustness or by an adaptive system.

Should the windings of the coil be not homogenous the field won't be homogenous too. This will result in a place dependent field and therefore a force which will vary also depending on the homogenity of the field. A good and carefully made coil is thus important.

It can be concluded that a coil should be used with the field in the direction of movement to enable maximal movability and the maximal range of control. In the centre of the coil the quartz tube should be placed in which the filament must be positioned.

3. The sensor

Due to the fact that the measurements have to be accurate and rather quick a laser sensor has been used. The type is a LX-130 model made by Keyence.

The sensor has been designed for measuring the area in between the emitting light source and the receiving sensor.

The light emitting source is a laser whose beam is emitted through a precise optical system which is intended to make a parallel light flux. After it leaves the lens it can be detected by the sensor who has a slit in front of its lens. The slit's height is 10 mm and is width is 1 mm. The lens of the receiver has to converge the beam onto the light sensitive sensor. If the beam between the light source and receiver has been interrupted and so causing a change in the light quantity, it renders an analog output depending on the area which interrupted the beam. The output voltage is linear between 5 V and 1 V which corresponds with an object area of 0 mm^2 and 10 mm^2.

The height of the filament can now be measured indirectly by interrupting the beam over its full width. The analog output renders now the area which is interrupted over a width of 1 mm and a certain height. This height is 10 mm minus the relative height of the filament.

The height is relative due to the fact that it is not possible to measure the filament but only the height of the lowest point of the sensor activating flag. This height is also relative to the zero level of the sensor.

The minimum size of the detectable object depends on the area that is interrupted. The resolution is 4 mV which matches, in this application, an accuracy in height of 10 μm. To guarantee accurate detection, taking into account the fluctuation in the output voltage due to the temperature changes, a change of at least 20 mV (50 μm) is necessary.

The response time is 0.5 ms which makes a sample-rate above 2 kHz useless.

The data acquisition card that has been used has a 12 bit accuracy on its analog inputs. This means that 1 LSB matches 1.22 mV or 3 μm while using the card in its 0 to 5V input range. This is good enough for an accurate measurement of the height.

This sensor has been chosen because it doesn't conflict with the operation principle of the positioning equipment. Other measurement equipment measures height by means of induction. This would inflict on the field of the coil which is used for positioning so those types couldn't be used.

During the experimental set-up this sensor has been used which worked just fine. However in a practical situation this sensor can't be used due to the fact that it requires an optical contact which isn't disturbed in any physical way (no glass either). As the filament itself is inside a quartztube this sensor can't be used. To cope with this problem a vision system should be implemented which measures the distance between the wanted position and the filaments actual position and thus rendering the input signal for the controller. This system can be used because it takes a picture of the actual proces and from this the distance can be calculated.

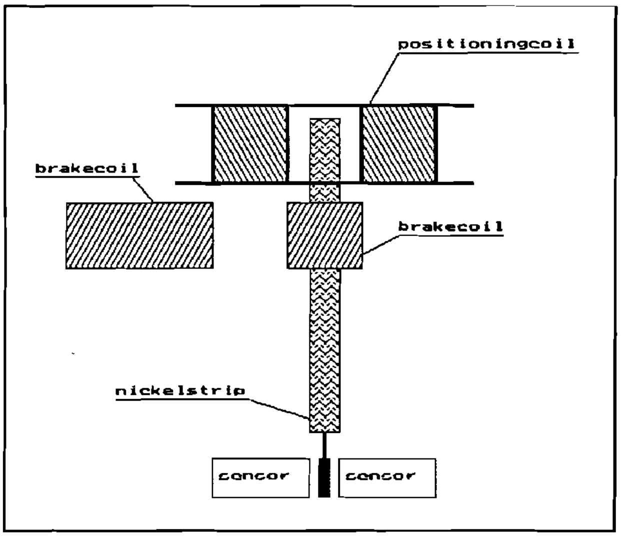


figure 3.1 : the laboraty set-up

4. Testing the principle

In order to test the principle a fuzzy controller has been designed. The choice of designing a fuzzy controller was made on base of its easiness of implementation. To design a controller based on fuzziness one doesn't have to do any identification nor is there a need of a model which describes the physical properties of the system.

The design of the controller is very easy and based on logical actions one should make if a certain situation should occur. This results in a two dimensional matrix in which the rows represent a certain speed and the columns a certain error of the position. Because only the height can be measured the velocity is the difference in height between two measurements divided by the sampletime. The values that have been edited into the matrix give the steppingrate of the current. For example if the error is zero, the position is correct, and the speed is zero then the current shouldn't change so the stepping rate is zero. In a similar way the rest of the matrix has been filled resulting in a matrix which could look like underneath.

error

velocity	nl	ne	ns	ze	ps	po	pl
nl				pl			
ne				po			
ns				ps			
ze	po	po	ps	ze	ns	ne	ne
ps				ns			
po				ne			
pl				nl			

nl = negative large

ne = negative

ns = negative small

ze = zero

ps = positive small

po = positive

pl = positive large

A negative speed means that the filament is moving down (i.e. falling), and a positive means it is moving up. In a similar way is the error implemented negative means that the filament is to low and positive means it is to high. Furthermore there are three gradations in both ways.

The controller hasn't been optimised for speed because this wasn't the objective. The only things that have been measured were the height, and its precision, and the time needed for a positioningcycle.

The results were that with this simple controller, its implementation was made during just a few hours, an accurate positioning was possible in the range of 50 to 100 μm. The disadvantage of this controller was its speed. It took over 5 seconds before a procesvalue was reached that matched the setpoint with the mentioned accuracy.

Because the sensor is more accurate than the accuracy that could be achieved a better and more carefully designed controller should be able to achieve a higher accuracy and a faster speed. But those objectives weren't the objectives which have been intended to achieve in this phase.

From the results it can be concluded that it has to be possible to position with a high speed and a high accuracy using a good designed controller. Also it shows that the principle of operation can be used for this positioning problem.

5. The physical model of the actuator

5.1. Deriving the equations

After the tests with the fuzzy controller in which it became clear that this principle could be used, a physical model should be made.

If the nickelstrip would have been positioned symmetrically inside the coil there won't be any force working on it because the magnetical energy wouldn't change (see figure 5.1). This is the situation where the magnetical field density is the largest inside the nickelstrip.

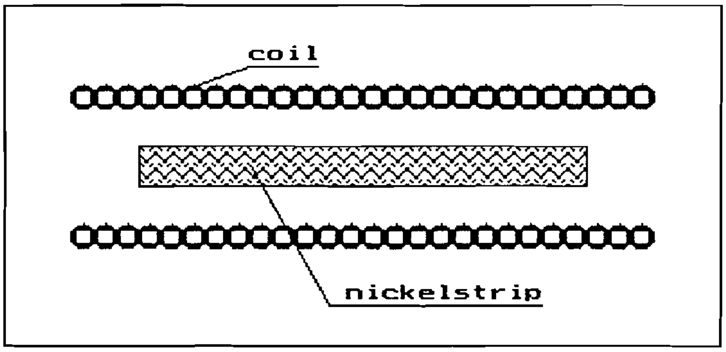


figure 5.1 : the nickelstrip in the coil without any force

If a situation should occur in which the nickelstrip wouldn't be in the coil anymore then a force would be generated trying to move the nickelstrip into the coil. Because in the practical situation a positioning is done in a vertical way the force pulling it out of the coil is the gravity force and a magnetical force is pulling it in again. Therefore a balanced situation can be achieved at which the nickelstrip won't move. In figure 5.2 this situation can be seen. The practical arrangement has been made in the same sense.

The magnetical field distribution of this arrangement is very complex because a part of the nickelstrip will be inside of the coil and another part is outside of it.

However to determine the quantity of the necessary force the totally magnetical energy doesn't need to be determined but just the change of it due to a movement over a distance Δx.

The total magnetical energy can be calculated by:

$$W = \frac{1}{2} * \int_V \overline{H} * \overline{B} \, dV$$

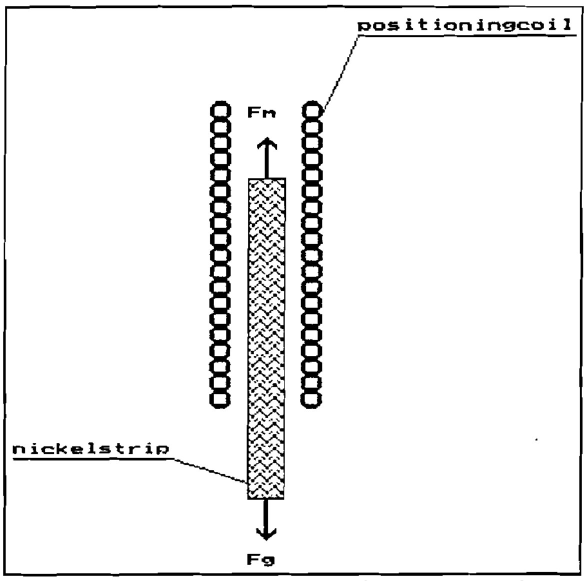


figure 5.2 : the nickelstrips
and the working forces

The primary field structure that has been excited by the current through the coil is homogenously distributed inside the coil.

Though the field structure is very complex in the inside of the coil it moves along with the nickelstrip as this strip is moving inward the coil. The most important difference between the two situations in figure 5.3a and 5.3b is that the nickelstrip has moved over a distance Δx into the coil. The totally energy has changed from $W(x_o)$ to $W(x_o+\Delta x)$.

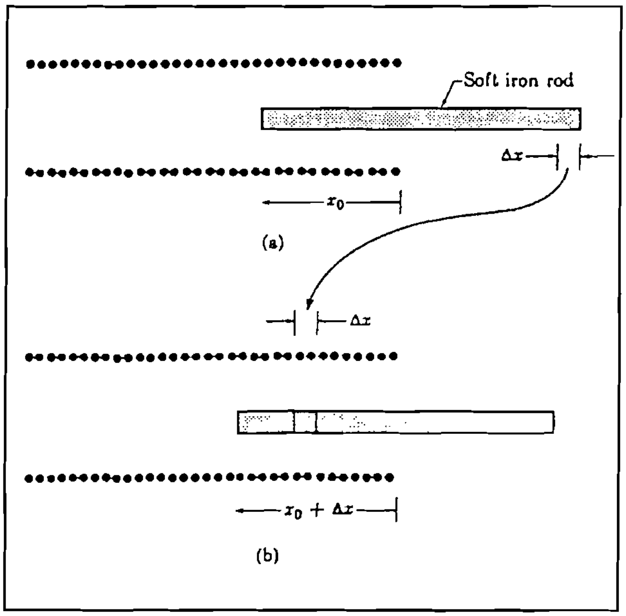
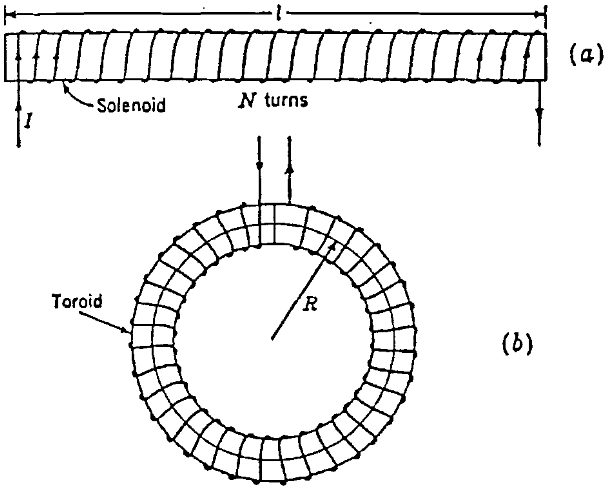


figure 5.3 : the movement of
the nickelstrip in the coil

By using the formula for the magnetical energy we can determine the magnetical force.

$$\oint \overline{H}\, d\overline{l} = I_{enclosed}$$

If the coil is deformed into a toroid as is shown in figure 5.4 the structure and the quantity of the field won't be changed.



(a) Long solenoid. (b) Solenoid bent into toroid.

figure 5.4 : the deformation into a toroid

In the case of the toroid the same formula can be used.

$$\oint \overline{H}\, d\overline{l} = I_{enclosed}$$

$$\oint \overline{H}\, d\overline{l} = H * \oint d\overline{l} = H * R * \int_{0}^{2\pi} d\phi = H * R * 2\pi$$

By entering 2*π*R=l this leads to:

$$\oint \overline{H}\, d\overline{l} = H * R * 2\pi = H * l$$

By assuming the length of the coil is l this expression can be also be used in the situation of the coil. The enclosed current $I_{enclosed}$ will be equal to N*I. This results in the equation:

$$\oint \overline{H}\, d\overline{l} = H * l = N * I$$

Because of the relation:

$$\overline{B} = \mu * \overline{H}$$

the magnetical energy can be calculated while assuming as the used volume A*Δx. This assumption combined with the previous relation renders the magnetical energy while linearising at x_o and a possible change Δx.

$$W(x_o+\Delta x) \approx W(x_o) + \frac{1}{2}\int_{A*\Delta x} (\mu-\mu_o) * \frac{N^2*I^2}{l^2}\, dV$$

This has lead to a magnetical energy at x_o+Δx which consists of a constant part $W(x_o)$ and a linearised part. The quantity of the linear part depends on the Δx. Further calculation results in:

$$W(x_o+\Delta x) \approx W(x_o) + \frac{1}{2} * (\mu-\mu_o) * \frac{N^2*I^2}{l^2} * A * \Delta x$$

The force which is projected onto the nickelstrip can be calculated by the derivation towards x of the magnetical energy.

$$F_m = \frac{W(x_o+\Delta x) - W(x_0)}{\Delta x} = \frac{\left(\frac{1}{2} * (\mu-\mu_o) * \frac{N^2*I^2}{l^2} * A * \Delta x\right)}{\Delta x}$$

So the relation for F_m equals:

$$F_m = \frac{1}{2} * (\mu-\mu_o) * \frac{N^2*I^2}{l^2} * A$$

This gives the possibility to control the acceleration in the desired direction. The generated force is F_m and the which is moving the nickelstrip down is F_g. The resulting force is therefore $F_m-F_g=m*a$, in which m is the mass of the total filament and a is the resulting acceleration up if it is positive and down if negative. The filament won't move if F_m equals F_g.

The only disadvantage of this system is the fact that the maximum upward acceleration is limited by the current through the coil (which could be very large during a short period of time) while on the contrary the maximum acceleration downward is limited by F_g which can't be controlled. This fact could limit the response of the total system and therefore there has to be paid attention to it while implementing the system.

5.2. The permeability

According to formula I which has been derived in the last section the force F_m is proportional with N^2, I^2, l^{-2} and μ. The N,I and l are parameters which are being determined by the dimensions of the coil but μ is determined by the magnetical properties of the nickelstrip.

The magnetical properties can be seen in figure 5.5.

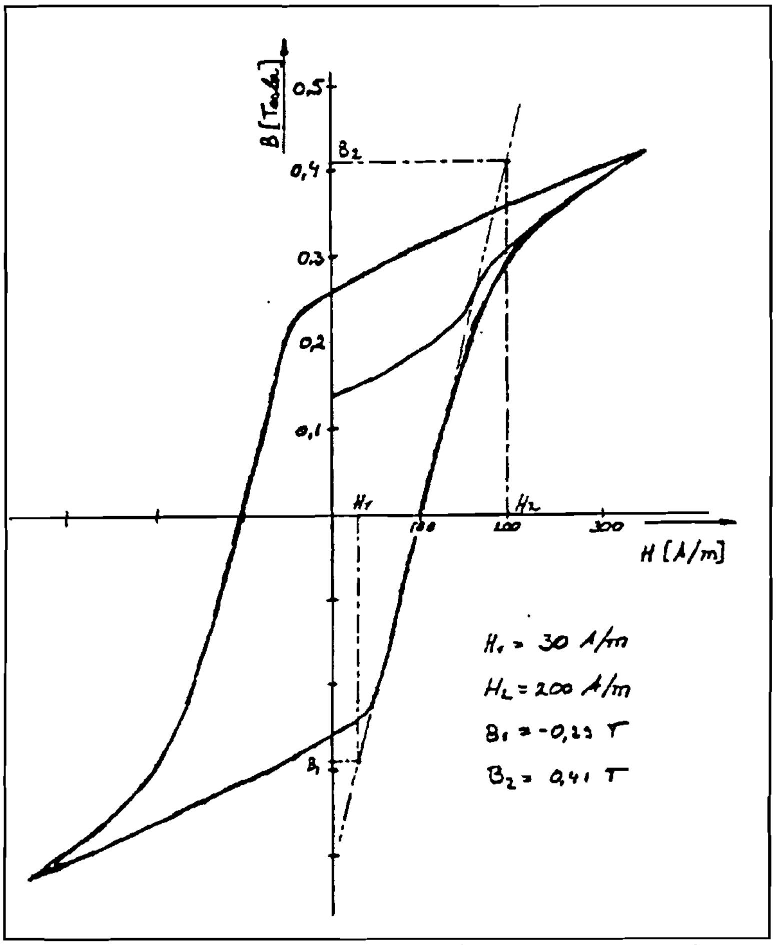


figure 5.5 : the magnetical properties of the nickelstrip

From the figure it shows that:

- H_1 = 30 A/m
- H_2 = 200 A/m
- B_1 = -0.29 Tesla
- B_2 = 0.41 Tesla

By using $B=\mu*H$ the value of μ can be calculated.

$$\mu = \frac{B}{H} = \frac{B_2 - B_1}{H_2 - H_1} = \frac{(0.41\ T) - (-0.29\ T)}{200\ A/m - 30\ A/m} \approx 4.1 * 10^{-3}\ \frac{kg * m}{s^2 * A^2}$$

The μ now can be used to dimension the coil.

5.3. The dimensioning of the coil

To dimension the coil it is necessary to make a few assumptions.

- the length of the coil is 4 cm because the length of the nickelstrip is 4 cm and this has therefore the largest controlrange
- the inside radius of the coil has to be at least 6 mm to assure a good fit of the quartztube
- the number of the Ampère-turns has to be chosen to assure that the nickelstrip won't move, which means a resulting force of 0 N. By changing the Ampère-turns the level of the magnetical force can be changed thus resulting in a positive resulting force, the nickelstrip starts accelerating upward, or a negative resulting force, the nickelstrip starts falling down. Because the force inside of the coil is constant and only changes due to the current, the resulting force 0 N can be achieved anywhere inside the coil by always the same current. Therefore it isn't necessary to calculate this force for one particular place.
- the mass of the total filament and the nickelstrip together is 0.4 gramm (F_g = 4 mN).
- the μ has been calculated in the previous paragraph and equals to $4.1*10^{-3}$ $kg*m*s^{-2}*A^{-2}$
- the crosssection A of the nickelstrip is 2.5 mm * 0.2 mm

While calculating the number of Ampère-turns the assumption is made that the nickelstrip is in its saturated area in the hysteresisloop. The magnetical field inside the nickelstrip corresponds to the next relation:

$$B = 2*10^{-4} * H + 0.25\ Tesla$$

By using this equation a H-field of 12000 A/m would be needed for a force of 5 mN.

The temperature of the coil is a very important parameter. If the temperature would be above a maximum the coil would burn and thus destroying itself. Should the temperature be to high for a longer period of time the coilbody could melt.

In the calculation it is therefore important to take this problem into consideration. The dissipated power is I^2*R in which R is the total resistance of the coil and is linear with the number of turns. However by increasing the number of turns the necessary current will decrease also linear with the number of turns.

$(N*I)^2$ = Constant
R = N * r   r is the resistance per turn

dissipation = I^2*R = (Constant / N^2) * (r*N) = Constant * r / N

If the number of turns is increased the current will decrease and also the dissipation. On the contrary a slight change in current would result in a larger change of the field and therefore a more difficult controllability. Another fact which hasn't been taken into account is the increasing radius as a result of the increasing N. The turns inside of the coil will lose their heat more difficult at an increased number of turns. This leads to a higher temperature and should be paid attention to.

By combining all the previous information with the maximum temperature for the coil, the coil can be dimensioned. This has led to a coil with the following dimensions:

- length = 40 mm
- inside radius = 6 mm
- number of turns = 500

5.4. The capturing of the nickelstrip

The nickelstrip is inserted into the quartztube and will fall over a few centimetres after which it has to be stopped and positioned. The braking is a problem which can't be coped using the positioning coil. As a solution to this two braking coils have been installed according to figure 5.6.

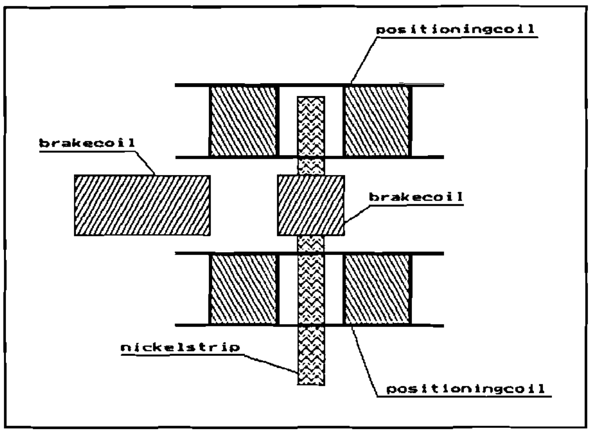


figure 5.6a : the arrangement with breaking coils

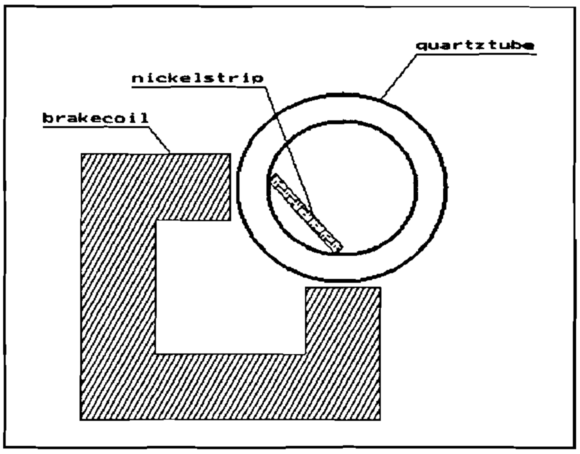


figure 5.6b : view from above

The brake and hold coils, which are the same, are perpendicular to each other and perpendicular to the direction of movement of the nickelstrip with filament. The field which comes out of one braking coil should go inside the other one, which can be achieved by an appropriate choice of the direction in which the current flows through the coil. This results in a larger braking force.

The operating principal is to increase the friction between the nickelstrip and the quartztube and so losing the energy which is present in the velocity of the nickelstrip and the filament. A smaller part of the energy will be lost in the form of eddy-currents due to the movement of the nickelstrip in the constant magnetical field.

If the coil's velocity has been decreased to zero the coils hold the nickelstrip and the positioningcoil can take over the positioning. The brake coils have to be switched off to enable the positioning.

The braking force has to be chosen to have a braking force which assures a constant braking and thus a small band of difference between the different nickelstrips. The nickelstrips should be held as close as possible to the desired position of the filament which makes a positioning over a larger range unnecessary and increases the speed.

Should the nickelstrip be larger the braking force should be increased by a larger current which holds the nickelstrip at a higher position but the filament, which is the object of the positioning, will be at the right place.

The position of the braking coils in the total arrangement should be in the center of the positioning coil. This enables a braking above the middle of the upper positioning coil and thus increases the range of positioning. This can be done because the field between two coils won't change to much if the distance would be small enough. Later it showed that using two coils didn't give any special advantage. In fact due to the instable lower half of the coil the combination didn't improve the system at all.

The arrangement that has been made consisted of:

- two coils of each 150 turns and 15 mm long and no core
- two coils of each 150 turns and a ferroxcube core

The core has to be of ferroxcube because it hasn't any remanent magnetism. This remanent magnetism could change the field of the positioning coil and would attract the nickelstrip thus increasing the friction.

5.5. The linearising of the equations

According to the equation for the magnetical force, this force is linear with I^2. If the controller should control I^2 a linearisation wouldn't be necessary.

A disadvantage however is the calculation of I from I^2. The error introduced by this step is very small and for the totally range bound to the same maximum which is very small. The error that would be introduced by a linearisation however would increase the further away the I is from its linearisationpoint I_0.

Therefore the decision was made to use the I^2 equations.

5.6. The state-space model

From the equation that has been determined in section 5.4 a state-space model can be set up.

The general form is:

$\underline{\dot{x}} = A\ \underline{x} + B\ \underline{u} + \underline{f}$
$\underline{y} = C\ \underline{x} + D\ \underline{u} + \underline{g}$

For the total state-space model all the forces have to be taken into account. This leads to:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ C \end{pmatrix} * i^2 + \begin{pmatrix} 0 \\ -g \end{pmatrix} + \underline{\xi}$$

$$y_1 = x_1 + 0 * i^2 + \zeta$$

In these formulas the symbols mean:

x_1 = x = the distance in which the nickelstrip is inside the coil
x_2 = $\dot{x}_1$ = the velocity of the nickelstrip
x_3 = $\ddot{x}_2$ = the acceleration of the nickelstrip
y_1 = the measured distance in which the nickelstrip is inside the coil

$C = \frac{1}{2} * (\mu - \mu_o) * N^2 * A / (l^2 * m)$

$\underline{\xi}$ = the error introduced by the actuator (state-error)
ς = the error introduced by the sensor (measurementerror)

6. Testing the model in a practical situation

6.1. The measurementresults

During the measurements at the implementation it showed that there is an obvious relation between position and force. The results can be seen in table 6.1 and figure 6.1.

height [mm]	current [A]
1.00	1.75
2.00	1.775
3.00	1.80
4.00	1.85
5.00	1.90
6.00	1.975
7.00	2.05
8.00	2.125
9.00	2.25

table 6.1 : relation between height
and necessary current

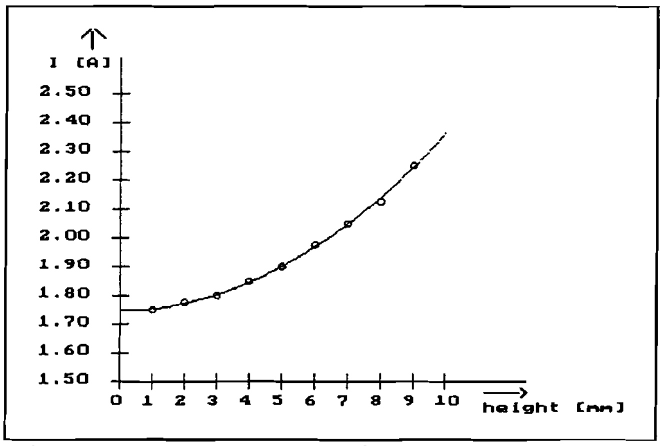


figure 6.1 : relation between
current and height

In figure 3.1 it is very obvious that the relation current-height isn't independent as has been calculated. In order to explain this graph a better model has to be derived.

6.2. Analysis of the results

In section 6.1 it became clear that the relation between I and F_m doesn't match the relation of the model. This means a better model has to be designed.

From the derivation in chapter 5 it can be seen that the force generated by the field changes if the field would change dependently of the position inside the coil. The model used does't have any position dependence, therefore a new model of the force starts with modelling the field again in a better way.

If the results are transformed to the field in the coil a relation as in figure 6.2 can be noticed which show a clear position dependence.

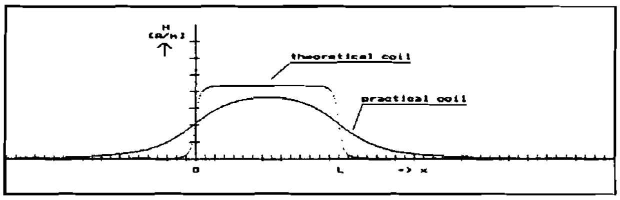


figure 6.2 : the field in the centre of the coils

A new model of the field and the resulting force will be given in the next chapter.

7. The new model

7.1. The derivation of the new model

For the derivation of this new and better model the law of Biot-Savart is being used. According to this law the contribution to the magnetical field as a result of a current in a piece of wire dl on a distance r is:

$$\overline{dH} = \frac{1}{4\pi} * \frac{I * \overline{dl} \times \overline{r}}{r^2}$$

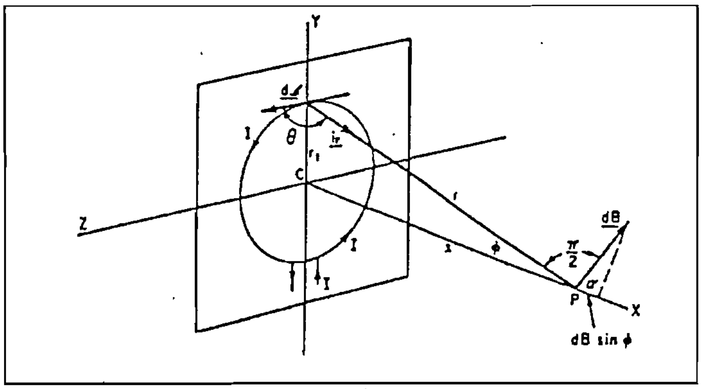


figure 7.1 : the field of one turn

By assuming a great number of turns that are very close to each other, and thus assuming that a coil is a combination of many single turns, the next calculations can be made.

Moving along the wire of this single turn, thin coil according to figure 7.1, won't change the size of dH but only the direction. The total resulting H will therefore be 0 in the y- and z-direction because a contribution dH at a certain point will be compensated in the y- and z-direction by a point π*r further along the wire. This results in a simplified solution by just determing the size of dH along the x-axis in the situation according to figure 7.1 and integrating this result over the length of the total wire.

In this situation dl equals to:

$$\overline{dl} = \begin{pmatrix} 0 \\ 0 \\ dl_3 \end{pmatrix}$$

Furthermore r equals:

$$\overline{r} = \begin{pmatrix} r \cos \phi \\ - r \cos \phi \\ 0 \end{pmatrix}$$

Which leads to:

$$d\overline{l} \times \overline{r} = \begin{pmatrix} 0 \\ 0 \\ dl_3 \end{pmatrix} \times \begin{pmatrix} r \cos \phi \\ -r \sin \phi \\ 0 \end{pmatrix} = \begin{pmatrix} dl_3 \; r \sin \phi \\ dl_3 \; r \cos \phi \\ 0 \end{pmatrix}$$

Entering this into the formula of the Biot-Savart law results in:

$$d\overline{H} = \frac{1}{4\pi} * I \begin{pmatrix} dl_3 \; r \sin \phi \\ dl_3 \; r \cos \phi \\ 0 \end{pmatrix}$$

The quantity of dH is:

$$dH = \frac{1}{4\pi} * I * dl_3 * r$$

Now dH can be divided up into a vector along the x-axis which quantity is dH*sinϕ and a vector in the YZ surface dH*cosϕ.

The integral along l leads to the total H in a point at the centreline.

$$\overline{H} = \frac{1}{4\pi} \oint \frac{I \; d\overline{l} \times \overline{r}}{r^3} = \frac{1}{4\pi} * \frac{I * r * \sin \phi}{r^3} \oint_l d\overline{l} = \frac{I \; r \sin\phi \; 2\pi R}{4\pi \; r^3} \underline{u}_x$$

This can be used to calculate the field in and outside of the coil. The field in a point along the axis is the summation of all field generated by the single turn coils which together make the coil that is being examined. Because the current has the same direction in all the turns the field will consist of positive contributions only.

The length of the examined coil is l and has N turns and a radius R (see figure 7.2).

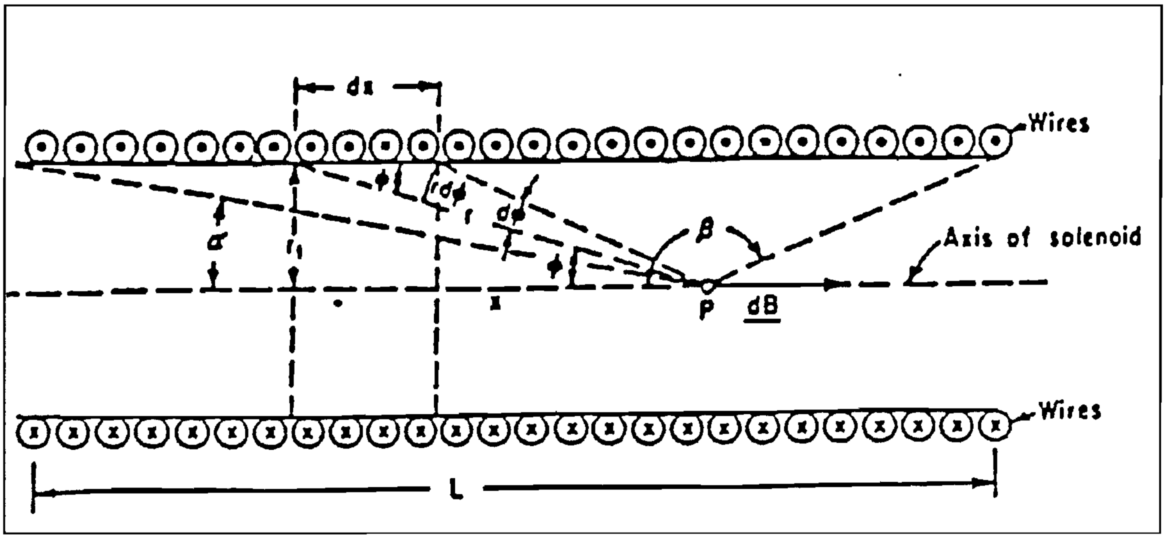


figure 7.2: the definition of the symbols in the coil

A part of the coil with length dx has N/l * dx turns which contributes dH to the field in point P on a distance r. The quantity of dH is:

$$dH = \frac{I * R}{2\, r^2} \sin \phi \, \frac{N}{l}\, dx$$

In which φ is the angle between the centreline and a line through P to the beginning of dx. Also dφ is the angle between the lines through the ends of dx and through P (see figure 7.2). If dx and dφ are very small the length r*dφ can be seen as a straight line and thus enabling the calculation of sinφ.

$$\frac{r\, d\phi}{dx} = \sin \phi$$

By also using R/r = sin ϕ the r can be eliminated.

$$\frac{r\, d\phi}{dx} = \sin \phi$$

$$\frac{R}{r} = \sin \phi$$

$$r = \frac{dx}{d\phi} \sin \phi = \frac{R}{\sin \phi}$$

The expression of dH can be rewritten into:

$$dH = \frac{I\, R}{2} \sin \phi\ \frac{N}{l}\ dx\ \frac{1}{\frac{dx}{d\phi} \sin \phi\ \frac{R}{\sin \phi}}$$

$$dH = \frac{I\, N}{2\, l} \sin \phi\ \ d\phi$$

By determing the sum of all contributions to H the field along the centre axis can be calculated. In this case ϕ runs from ϕ=α upto ϕ=β. The limit dϕ goes to 0 leads to:

$$H = \int_{\alpha}^{\beta} \frac{I\, N}{2l} \sin \phi\ \ d\phi = - \frac{I\, N}{2l} \cos \phi \Big|_{\alpha}^{\beta}$$

$$H = \frac{I\, N}{2l} \left(\cos \alpha - \cos \beta \right)$$

The quantity of the field can be seen in figure 7.3.

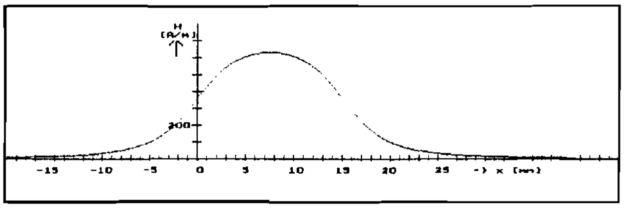


figure 7.3 : the field as a function of the place

In this figure a coil has been used with l = 15 mm, I = 1.5 A and R = 5 mm. The x is the distance inside the coil.

By using this formula for H an accurate calculation can be made of the forces generated by the coil.

To determine the force on the nickelstrip the same method is being used as before, only the difference in energy between two situations is being calculated if the nickelstrip has been moved a distance Δx.

The magnetical energy equals:

$$W = \frac{1}{2} * \int_V \overline{H} * \overline{B}\, dV$$

By assuming that B can be accurately described by the formula for the saturating area, a much easier formula can be used. Numerical analyses have showed that this step could be done without changing the result significantly.

The magnetical energy can then be calculated from:

$$W = \frac{1}{2} * \int_V \overline{H} * \overline{B}\, dV = \frac{1}{2} * \int_V \overline{H} * (2*10^{-4} * \overline{H} + 0.25)\, dV$$

Because the force is change of energy (ΔW) due to a change of position (Δx) it is only necessary to calculate the changing of the energy. The energy is mainly changed by the following mechanisms:

1) an increase as a result from moving the head of the nickelstrip further into the field

2) a decrease from the end of the strip because it moves a distance Δx and thus leaving a certain field

3) an increase in the energy in he air as a result from the movement of the end of the strip

4) a decrease from the energy in the air due to the movement of the head of the strip

The effects 1 and 2 will be the largest because the main part of the energy will be concentrated in the nickelstrip. During the movement of the strip until it has reached the centre of the coil effect 1 is the most important. From this point on the effect 2 will become more important and thus decreasing the energy in the nickelstrip.

The difference in magnetical energy is:

$$\Delta W(x) = W(x) - W(x-\Delta x)$$

The magnetical energy that matches each part of the strip can be calculated from a volume integral over the surface from the nickelstrip multiplied with the movement Δx. This further calculating leads to:

$$W(x) = \int_{A\,*\,\Delta x} \overline{H} * \overline{B}\, dV = \int_{\Delta x} A * \overline{H} * \overline{B}\, dx$$

The magnetical force calculated with this is therefore equal to:

$$F(x) = \frac{A*\Delta x*H(x)*B(x) - A*\Delta x*H(x\text{-}length\ strip)*B(x\text{-}length\ strip)}{\Delta x}$$

$$H(x) = \frac{N * I}{2 * l} (\cos\alpha - \cos\beta) = \frac{N * I}{2 * l}\left(\frac{(l - x)}{\sqrt{R^2 + (l-x)^2}} + \frac{x}{\sqrt{R^2 + x^2}}\right)$$

$$B(x) = 2 * 10^{-4} * H + 0.25\ Tesla$$

Which leads to:

$$F(x) = \frac{1}{2} A * \{ H(x) * B(x) - \ldots$$

$$\ldots - H(x - length\_strip) * B(x - length\_strip) \}$$

$$F(x) = \frac{1}{2} A \{ 2*10^{-4} [H^2(x) - H^2(x-length-strip)] + \ldots$$

$$\ldots + 0.25 [H(x) - H(x-length\_strip)] \}$$

In figure 7.4 this force has been put into a graph. The coil calculated with has 150 turns, I = 1.75 A and l = 15 mm.

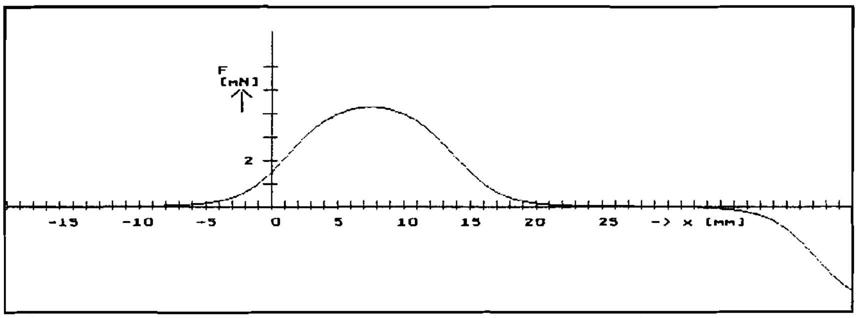


figure 7.4 : the force from a coil

7.2. The useful area in the forcegraph

By examining the graph of the force more carefully it can be noticed that it consists of two different areas:

1) a stable area in which the force decreases if the nickelstrip should move up, and increases if the strip should move down

2) an unstable area in which the force increases for an increasing height and decreases if the strip moves down

The stable area runs from the half of the coil upward while the instable area runs from the half downward.

These two areas could be noticed during the experiment which have done before. Using a fast controller resulted in an unstable system because the controller tried to compensate the error using a large signal. This would result in an overshoot into the stable area at which the controller reacted by decreasing the signal and let the nickelstrip drop down, next he tried to move it up, etc.

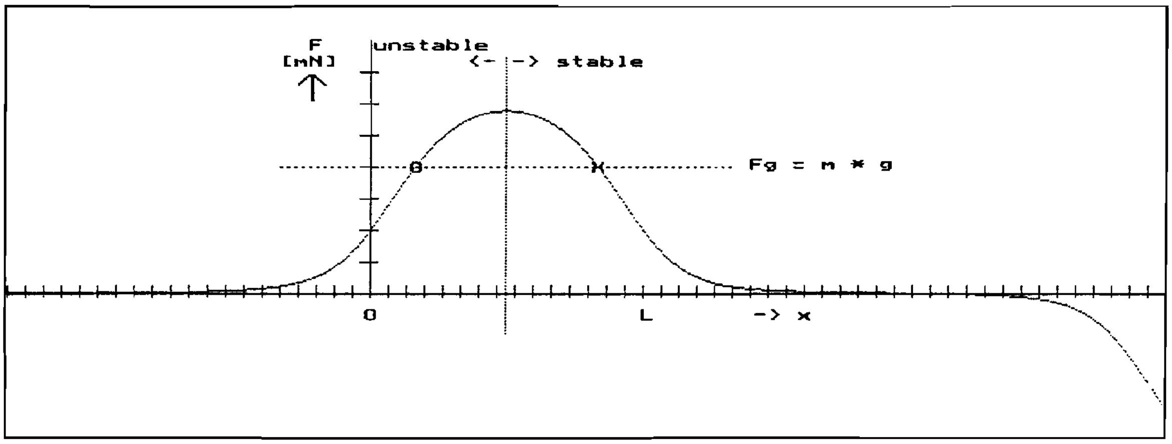


figure 7.5 : the two areas in the force graph

The situation in which the coil won't move at all is if the line drawn by the force in the coil crosses the line which represents the gravity force. This renders two points: one in the stable area, represented in figure 7.5 by an X, and one in the unstable, represented by an O. The controller and the designer of the implementation have to take care of the fact that the head of the nickelstrip only moves in the stable area during the total positioning cycle.

By increasing the current through the coil the magnetical force graph will be lifted and the points X and O, where the two lines cross, will change. In figure 7.5 this can be seen in the movement of the points X and O. By increasing the current I the graph of the force will lift and therefore moving the point of intersection toward the edge of the coil (see figure 7.6). This results in an inverse reaction in the lower half of the coil.

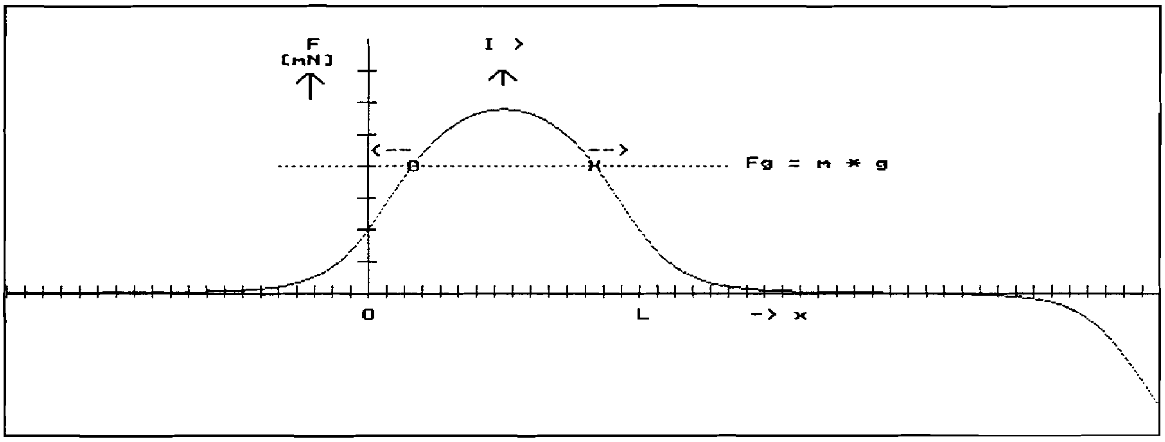


figure 7.6 : the changes due to an increasing current

An increased current results here in an increased force, which makes the nickelstrip move up until it has reached the next stable point. This point will be in the stable area which is too far up. To move the nickelstrip up in the instable part an increase is necessary followed by a decrease of the current to an even smaller value then started with. The increase will make the nickelstrip move up but the decrease will assure that it won't move too far up and therefore ending in the stable area. The increase is necessary because a decrease would result in a force in the starting position that would point down and therefore result in a movement of the nickelstrip downward. In the same sense an inverse action is needed for lowering the nickelstrip.

This inverse reaction in the lower half of the coil therefore results in a instable part which isn't preferred to use in the implementation because it is combined with the fact that a slight movement of the nickelstrip results in a changed force in the wrong direction. A movement up results in an upward force which accelerates the nickelstrip even further upward and a downward movement results in dropping the nickelstrip.

However in the upper half an increased current results in a movement upward to a new stable point. This principle of operation can be used by the future controller.

8. Analysing the results

8.1. Comparing the measurements with the model

Comparing the results from the measurements shows a good correspondence between the model and the values measured. The differences have resulted from:

- errors while reading the meters
- friction between nickelstrip and the quartztube
- an effective inside radius which is larger than the inside radius of the coil. This is a result of the layers of the coil while the calculations made just counted one layer. This results in another field distribution and a slightly smaller field.
- the nickelstrip is positioned against the quartztube where the field has another direction and quantity
- the calculations assume a field which only changes in the z-axis and not in the x- or y-axis (this is the horizontal area inside the nickelstrip). This isn't correct either because the calculated H-field only resemble the field on the centre line. However the magnetic conduction of the nickel is that good the field doesn't change too much.

Now a good model has been achieved which matches the results very good.

8.2. Further improvement of the model

Comparing the model with the measured values shows that the model does resemble the practical situation with only a slight difference. However if instead a coil with 150 turns 10 coils with each 15 turn are simulated the model fits even better. In figure 8.1 this situation can be seen. Noticeable is the fact that especially in the range from 0 to 5 mm the fit is very good. The difference in the higher region has been caused by the fact that the coil will behave more and more as an ideal coil with a rod inside. This will result in a changed field which hasn't taken into account in the simulationprogramm which has been written especially for this project.

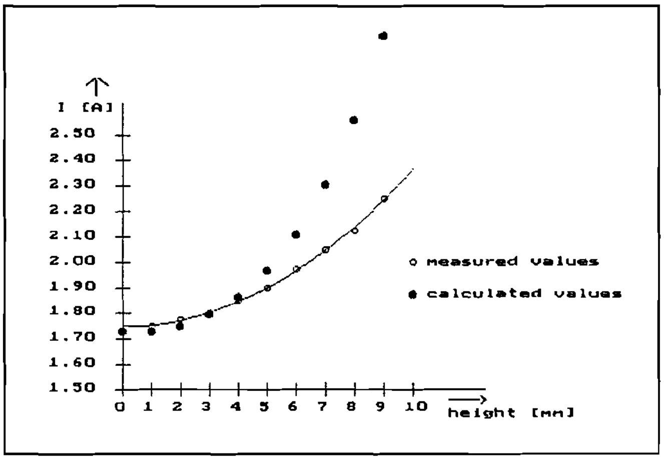


figure 8.1 : current-height relation

In the higher region the necessary current is smaller due to the more homogenous field. A practical coil has a field which is more similar to that of figure 4.9 while an ideal coil has a field which only leaves the coil at the ends.

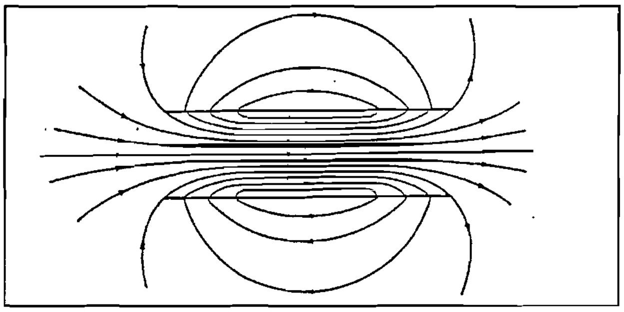


figure 8.2 : the field of a practical coil

Because of the more homogenous field the resulting force upward will be increased and therefore a smaller current is needed.

9. Two coils situation

In this situation it is also desirable to split the coil in half in order to place the brake- and hold-coils in the centre.

The effect of this situation can be seen in figure 9.1 and have been calculated in the same way as the force for one coil. Because a magnetical field can be added this situation is the same as calculated before. The coils used are two coils 15 mm long and each 150 turns.

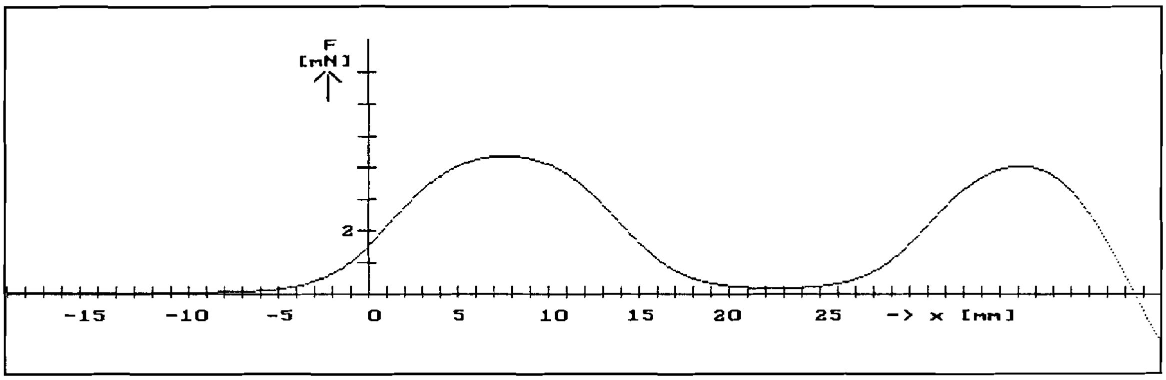


figure 9.1 : the force due to two coils

A better analysis of the formula used shows that the only situation which renders a constant force in between the two coils is when the distance between the coils added up to the length matches the radius. This would mean in this situation:

- coil length = 15 mm
- distance = 10 mm
- and therefore radius = 25 mm

This would, however, mean that the total force would decrease a lot (see figure 9.2).

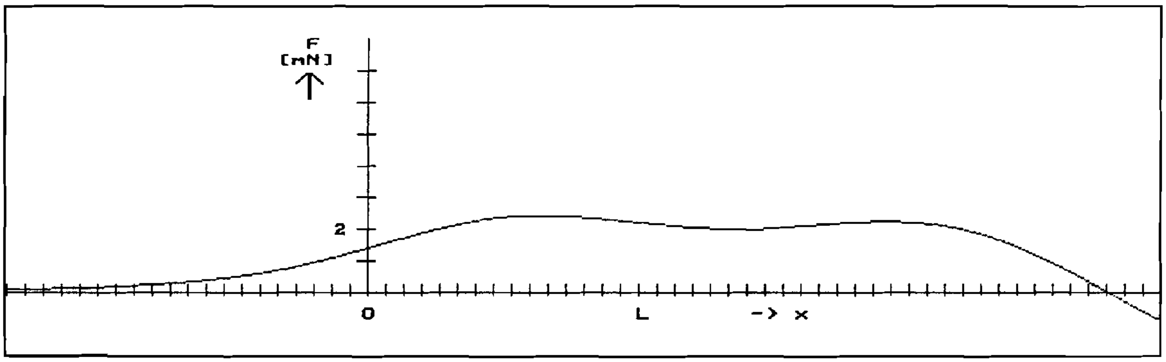


figure 9.2 : force with two coils with increased radius

10. Controllerdemands

In order to design the controller a number of objectives have to be made.

One of the things that have to be reached is the productionspeed which is 0.5 seconds per lamp. This contains the injection of the filament, the positioning and the melting of the lamps in order to close it.

The injection has to be done by means of a free fall. The total filament falls over a distance of approximately 10 cm which should take about 0.15 seconds.

Assuming the closing of the lamps takes about 0.3 seconds leaves for the positioning 0.15 seconds. In this period of time the filament has to be positioned and its position has to be stabilised.

Influences who could be important are:

- variances in the mass of the nickelstrip and the filament. This would mean other dynamics and therefore another ideal controller.
- variances in the length of the nickelstrip and the filament. This will also result in a change of dynamics.
- a gassflow which is used to clean the inside of the quartztube from unwanted atoms. The flow will create an external influence which is disturbing the positioning sequence. This flow will also change the dynamical behaviour of the system because it will cause an upward force if the flow is upward (the resulting force downward will decrease) or a downward force if the flow is down (the resulting force downward will be increased).
- also a difference in magnetical properties will result in changed dynamics. Due to the manipulations previous to the positioning the magnetical properties will be influenced. A disturbance during the melting or a deformation of the basematerial will result in a changed magnetical behaviour. Another problem could be a change of material at all.
- the roughness of the surface of the nickelstrip will cause another frictionforce and therefore other dynamics. A changed force will be necessary to move the filament.

- the magnetical properties depend on the temperature of the material on the moment of positioning. Because the positioning takes place during the melting of the quartztube a change in dynamics can be expected.

The accuracy wanted will be kept at approximately 20 µm, which is the accuracy of the sensor used.

11. Implementation of the controller

11.1. The first design

Due to the strongly non-linear behaviour of the electromagnetical actuator, different reponses can be expected in the total positioning range, depending on the momentary position. A way to compensate this non-linear behaviour would mean improving the response significantly, because the controller would only have to cope with the dynamics and a slightly non-linear behaviour.

To assure a good statical tracking a model of the actuator can be used which describes the statical, strongly non-linear behaviour of the system. Implementing the inverse of this model as a feed-forward controller would mean a good statical behaviour. The model of the actuator can be determined by statical measurements which include the height as a function of the applied current (current as input and height as output of the actuator).

This renders a table which can be transformed into an analytical formula. Inversing this formula would give a possibility of calculating the necessary current at each height.

Measurements showed that the relation between current and height is a very simple quadratic formula. The parameters can be determined using Matlab (see figure 8.1). The formula which should be found looks like:

$$I = a * (x - h_0)^2 + I_0$$

In this formula I_0 is the value of the current which is at least needed to hold the nickelstrip in the coil. The position corresponding whith this current is that the head of the nickelstrip is exactly in the middle of the coil. The height h_0 is the height measured by the sensor when the current I_0 is applied to the actuator (see figure 11.1). To have the best response of the system it should be preferred that this height is negative due to the fact that this would mean the nickelstrip would always move in the stable area for a positive height. The current I_0 matches the minimum of the quadratic current height relation, or in other words the top of the force graph as a function of the position of the nickelstrip's head, and therefore a negative h_0 would mean that the head of the nickelstrip would always stay in the stable region. A negative height h_0 would mean that the current necessary would always be monotonously rising from the zero level upward. Therefore the inverse action as described in chapter 7.2 doesn't occur and the controller can be kept the same. Further this means that the change of height would implement a large change of the force excited on the nickelstrip. This results in a more stable system and a good suppression of the disturbances.

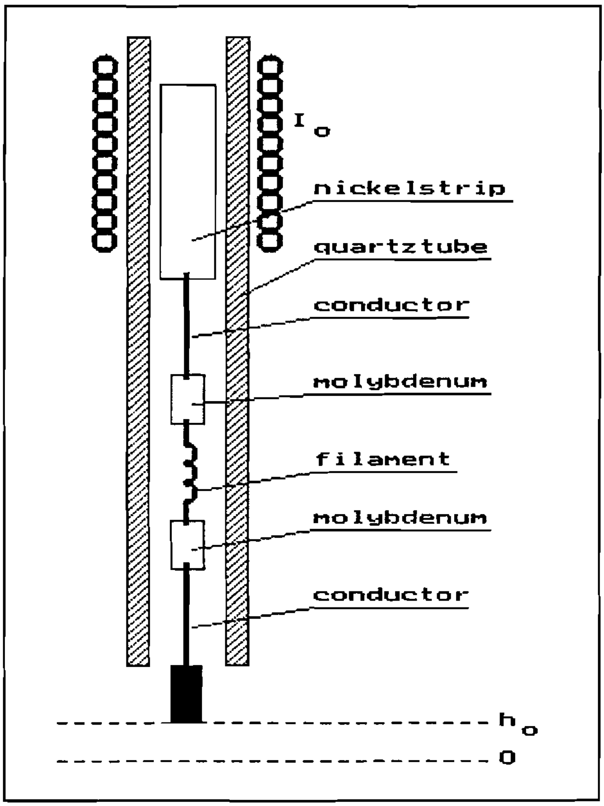


figure 11.1 : definition of h_o

The formula can be rewritten to:

$I = a * x^2 + b * x + c$

By entering the wanted height of the filament into this formula the necessary current can be calculated. The wanted height is the height relative to the zero level of the formula which has been derived. This should move the nickelstrip, and therefore also the filament, which is the object of positioning, towards a position near to the wanted position. This implemented in a feed-forward controller offers the possibility of statical positioning which means that if there wouldn't be any (dynamical) disturbance the calculated current would position the filament correct.

The formula of the implemented system was:

- $I = 0.023 * x^2 + 0.0025 * x + 1.8869$ (by MATLAB's curvefit)

x = the (wanted) height in mm
I = the necessary current

However, due to the dynamics of the total system and the dynamical disturbances a controller with a feed-back is needed.

In order to ensure a statical error of zero between the wanted and the measured height, an integrating action has to be implemented. The error is a result of the differences in length between different nickelstrips plus filaments.The statical description of the actuator doesn't ensure that there isn't a statical error. The feed forward control only assures that the position is near the wanted position but doesn't move the nickelstrip to reduce the error.

The actuator consists of two integrating poles (only the acceleration can be controlled up to a certain point where the resulting force is zero again). The gain of the system changes as the nickelstrip is moving in the coil. If the current increases the gain is increased also which results in the movement of the nickelstrip. The nickelstrip will move until it has reached a stable position in which the resulting force will be zero. In this point the gain has reached another stable value.

Furthermore to get a quick response on disturbances a differentiating action has to be build into the controller.

These thoughts lead to the choice of a PID-controller. This controller now adds a small signal to the output of the inverse model referenced control signal in order to decrease the position error.

Though the system is still non linear it showed that a PID-controller has to be used. The total system consists now of three poles (two from the actuator and one of the PID controller) and one zero point. The root locus, of a linear system, will look as in figure 11.2.

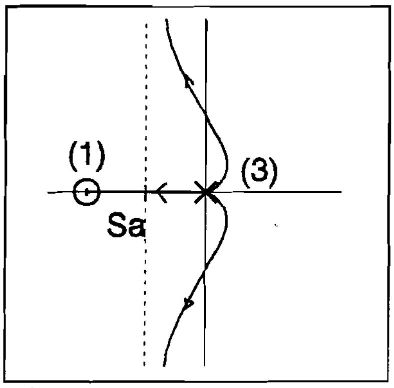


figure 11.2 : root locus plot

The point Sa equals to:

$$Sa = \frac{-\sum p_i + \sum z_i}{n_p - n_z}$$

All the poles are located in the origin and the zero point is located on the left of the zero axis. Also the number of poles (3) is larger than the number of zero points (1). Therefore the point Sa will be located left of the zero axis at - $z_d/2$. This means that for a sufficient large gain the system will become stable. All this holds for a linear system. Despite of the fact that the real system is essentially non-linear, the theory will not be valid. Nevertheless trial and error resulted in the next parameters of the controller which rendered the results as shown in appendix III.

- T_{sample} = 0.0005 sec.
- τ_i = 0.5/T_{sample} sec.
- τ_d = 0.1/T_{sample} sec.
- K = 5

In figure 11.3 the total configuration can be seen.

The two different signals can be seen: the current I which is generated from the non-linear controller and thus enabling the use of a simple linear controller which contributes i to the actuator current I_a.

The proces consists only of one positioning coil with the braking coils mounted underneath. This has been done because in chapter 9 it showed that using two coils didn't offer any better characteristics. This resulted in a configuration as shown in figure 11.4.

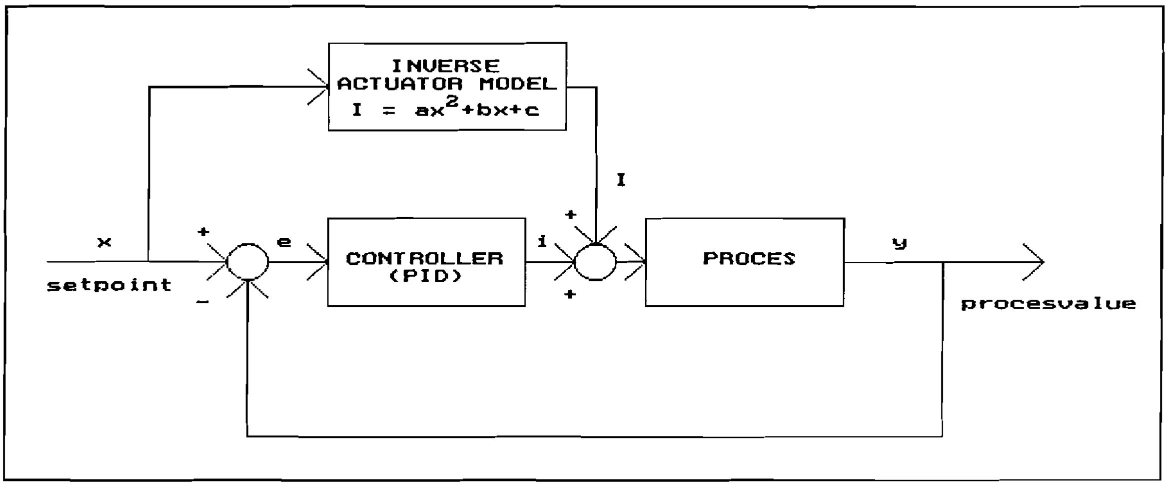


figure 11.3 : the implementation

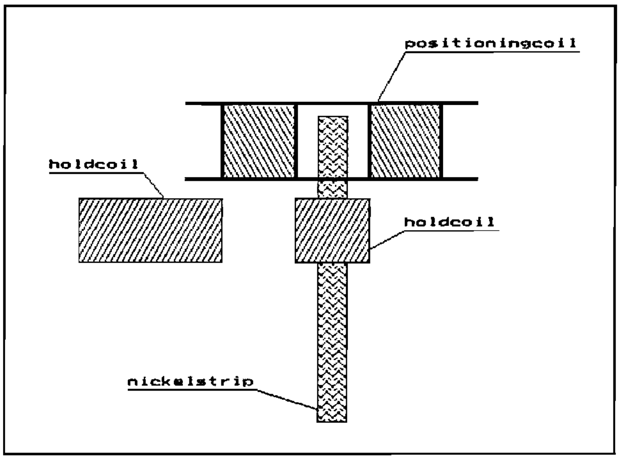


figure 11.4 : the definite implementation

This implementation renders very good results, however because the system is badly damped, due to the minor friction, it takes a rather long time before it has reached its statical situation. The controller designed can't be to fast because this would result in a very nervous behaviour or in an even worse damped system, see appendix III.

To solve this problem a second approach has been used. Which is discussed in the next section.

11.2. The definite system

To solve the problem of the badly damped system a low pass filter has been used (see figure 11.5). This ensures that there aren't any fast changing setpoint signals which could cause any problems.

The used lowpass filter is a second order filter with two the same poles and has the following form.

$$H(s) = \frac{1}{(1 + \tau s)^2}$$

The value of τ is 0.05 seconds. This lowpass filter has been implemented in software and is therefore a digital lowpass filter but the parameters haven't been changed.

The filter is designed in such a way that the system can follow the maximal ramp due to a step on the input (set point). This results in a better tracking behaviour and an enhanced response on a step. The system doesn't have any overshoot and the response is very fast.

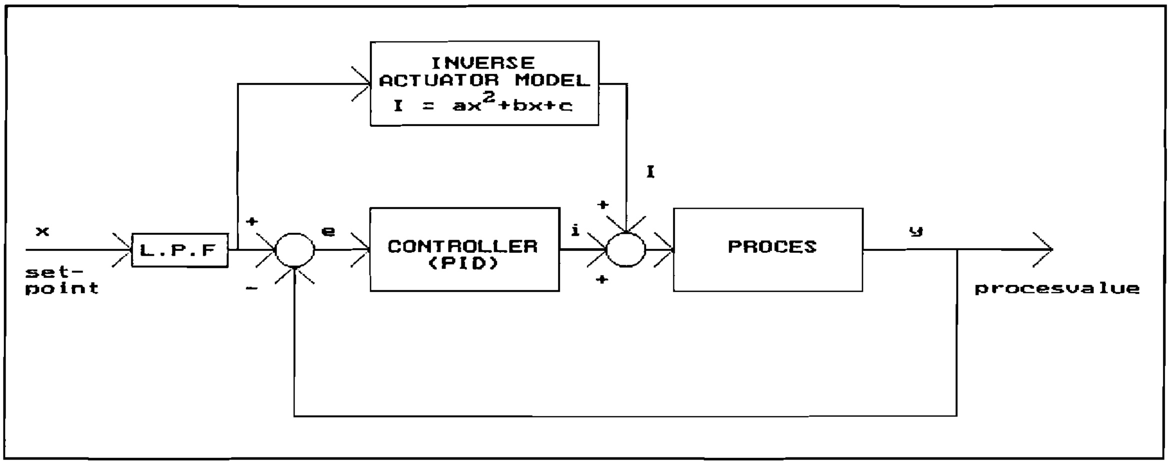


figure 11.5 : the definite system

Testing this system showed that the responses were very fast (0.1 upto 0.15 seconds per step), see appendix V. These times are the result of a larger step (8 mm) while in practice a step of maximum 4 mm is required.

Measurements of the height after the nickelstrips have been braked but not positioned, gave the following results:

- strip I : 20 measurements - average height = 3.465 mm
  - standard deviation = 2.712 mm

- strip II : 20 measurements - average height = 3.996 mm
  - standard deviation = 3.111 mm
- strip III : 20 measurements - average height = 3.217 mm
  - standard deviation = 2.373 mm

These tests showed that the nickelstrip can be braked within a range of approximately 6 mm after which a step of a maximum of 3 mm is necessary to position the filament. If the right position is at 0 mm the range in which the nickelstrip can be caught is between -4 and +4 mm. However in the most situations an ever smaller step has to be made.

The implementation of the system and the controllers haven't changed, also the parameters of the controllers are unchanged. Responses of this system can be seen in appendix IV. In this implementation, and also in the implementation of the previous section, the braking and positioning haven't been combined yet.

12. Test results

In appendix III some results can be seen. It is obvious that the system responds very fast and as accurate as possible, which means that the accuracy is only determined by the sensor. The controller which has been designed is a simple PID controller but the results are very good. The tuning of the controller has been described in chapter 11.1 and 11.2 and the parameters that have been mentioned there haven't been changed.

In the graphs it can be seen that the system, in the way it has been implemented, offers good results. Responses that are very fast can easily be achieved. Furthermore the accuracy is no problem.

The results have been tested with two different nickelstrips but with the same parameters of the controller. This has been done to have an idea of the practical situation in which one controller will be used for positioning thousands of different filaments. The nickelstrips used where strips that were just inside the tolerance borders, one on the maximum side and the other on the minimal side. Therefore the results can count as the borders in which the results of the other nickelstrips will fall. The slight difference in response can be seen but the response time is almost the same.

Things that can be noticed are the different responses in each region and the good tracking though there are two different strips.

If just one nickelstrip is considered the different responses in each region can be noticed which result from the strongly non-linear characteristics.

13. The braking and controlling

In order to demonstrate a total automated system the braking and positioning have been combined into one action.

The first thing that the controller does is activating the positioningcoil and the brakingcoil. This is done to ensure they have both had enough time to accumulate enough energy to brake the nickelstrip. Then the nickelstrip is released by an electromagnet which has been controlled by the computer also (switched on when the program is started and switched off when the braking and positioning cycle is started).

Next step is to measure the velocity by comparing two succeeding height measurement values. If the velocity has decreased enough then the positioning starts.

First the actual height is being measured from which the necessary current can be calculated. Then this current is applied to the coil and the brakingcoils are switched off in order to release the nickelstrip and enable the positioning coil to do its job.

The height is again being measured in order to eliminate the error of the model in this phase. This step has been implemented to start from a steady state without having the effects of the startup sequence which result in a nervous reaction of the controller due to the fact that it isn't a previous control action.

Finally the positioning takes place and the controller is holding the nickelstrip in its position.

From the graphs in appendix IV it shows that a total response of approximately 0.4 seconds can be achieved. The response consists of about 0.15 seconds for the braking and about 0.15 seconds for the positioning and stabilizing of the position. These times are conform the goals that have been set before.

The equivalent time structure is:

T < 0 : turn on electro magnet in order to hold the filament
turn on brake coil

T = 0 : turn off electro magnet and release filament

T = 0+ : measure velocity until it is small enough which
means that the brake coils can be turned of
(T = approx. 0.15 sec.)

T = 0++ : positioning starts: measure height, set all errors to zero, set the current through the coil equal to the current which can be calculated by the model using the measured height and turn off the brake coil

T > 0++ : the controller positions the filament

A complete description of the total positioning sequence and the practical implementation can be read in chapter 15.

From the figures in appendix IV the different stages of positioning can be seen. The horizontal scale is 0.1 seconds. For the first 0.1 to 0.15 seconds a height of 10 mm is measured. Because this corresponds with the maximum measurable height this means that the nickelstrip is above 10 mm. This is during the time needed to fall from the release by the electromagnet until it enters the measurement range. The distance over which the nickelstrip falls is about 10 cm which would take approximately 0.15 seconds. However, because the positioningcoil has been switched on, an extra force is excited on the nickelstrip that accelerates it downward. This has a positive effect in the shorter injection time, however the negative effect is that the coil has more energy which makes it harder to brake. The disadvantage isn't that large and during the measurements it showed that the braking coils could handle it very well.

14. Comparing mechanical positioning with contactfree

Comparing the mechanical positioning systems with this newly designed one leads to the next results.

The speed of a mechanical one is, after the insertion of the filament, just over one second. The contactfree positioning needs just about 0.15 second (at its maximum).

The accuracy of the mechanical system is mainly determined by the accuracy of the mechanics. This means the accuracy by which the gears have been made, the step size of the stepper motor, etc. determine the stepsize of the total system and restrict it to one certain length. Decreasing the stepsize would mean increasing the accuracy but the speed would decrease also the system would become more expensive.

The contactfree system doesn't have any restriction on the stepsize. The smallest step that could matter could be a result of the friction (stick and slip) but the stepsize of the current could be chosen to be so small that increasing the current by this step wouldn't have any effect on the total (this means no moving of the nickelstrip). Furthermore if the friction due to stick and slip would be a problem, some piezo transducers could be used which move the quartztube perpendicular to the positioning direction. This has to be done with a high frequency and within a very small range (less than approximately 100 μm).

Another advantage of the contactfree positioning is that if the system would have an overshoot it can be corrected by the controller, however the mechanical system doesn't offer this possibility and this therefore means the loss of a single product.

The price ticket of the mechanical system is high (approximately 150.000,= dollars) while the contactfree system is rather cheap (approximately 10.000,= dollars which includes the necessary power supplies, the making of the coil and the implementing of the total system in the production line) and easy to make and construct.

From these points of view the choice between mechanical and contactfree is rather easy to make: contactfree.

15. Some remarks on the practical implementation

15.1 Dimensioning of the mechanical parts

In this chapter the implementation as a working device will be discussed. This can be used as a guidance for future use of the designed and tested system. This chapter can also be used as a guidance for a future project in which the method but not the whole system is used and therefore a guideline is being presented. Because for the implementation the mathematical model of the electro magnetic actuator isn't needed, it won't be mentioned. For everyone interested in this area a reference is being made to chapter 7 of this report.

Of all the orientations and sizes an overview can be found in appendix VII. This appendix should be used while reading this chapter. The figures will be referred to as figure VII.x.

The necessary information which should be collected prior to the implementation is:

- the range of positioning: this means the maximum range in which the filament can move in the worst case. If for example the filament can move from -5 mm to +5 mm then the range is 10 mm
- the magnetical properties: this implies the hysteresisloop of the nickelstrip on which the magnetical force is excited
- the total mass of the filament and the nickelstrip, this includes everything which is attached to the nickelstrip
- the wanted holding current: if for example the desired current is 1 A this could imply that a small step of the current results in a large change of the force
- the position inside the coil at which to hold the nickelstrip while applying the wanted holding current
- the length of the nickelstrip
- the area of the nickelstrip
- the outside diameter of the quartztube
- the inside diameter of the coil including the thickness of the wall. The thickness of the wall should be taken twice into account because the inside diameter of the coil contains: the wall of the coilbody, the quartztube and again the wall of the coilbody
- the total length of the nickelstrip including the filament. This means the length from the top until the bottom.

The first step is designing the positioning coil. The length and the number of turns have to be chosen. The determination of the length is easy. The length of the coil is twice the range in which the positioning has to be done. However, in order to have a quick response and no effect of tolerances which could cause the nickelstrip to enter the instable area (see chapter 7) the length should be a bit longer. This yields in a length of approximately 2.5 times the range.

The number of turns can be calculated using a program written in Turbo Pascal V6.0 or by calculating it by hand. The program requires as input:

- the desired current
- the magnetical properties
- the length of the nickelstrip (or of the magnetical soft metal which is being moved)
- the area of the nickelstrip on which the magnetical force is generated
- the wanted height at which to hold it using the desired current
- the length of the coil
- the inside diameter of the coil, this diameter has to include twice the wall thickness of the coil body (so the real radius is meant by this)

The number of turns can also be calculated by hand but this isn't recommended because this would mean using the non-linear formula of the magnetical properties and calculate each area of its own. For using this program see the manual that is accompanied by the program.

Next the coil body has to be made on which the coil will be wound. It is very important to choose the right material because the coil body can get very hot. The sizes that are now important are the length of the coil, the thickness of the coil body and the radius of the tube inside the coil (see figure VII.1).

If the orientation of the nickelstrip is important then the positioningcoil should be equipped with two cores that are opposite of each other and run from north pole to south pole outside of the positioningcoil (see figure VII.2).

After the coil has been made its input-output relation has to be measured. As input there is the current and the output is the height. The height measured has to be the height of the filament relative to a zero level. This zero level has to be picked as a minimal level at which the filament can be caught during normal operation. This level has to be at least at a distance of the total length of the nickelstrip and filament from the centre of the coil, but preferably higher. At this point measurements have to be done carefully resulting in a table which describe the height-current relation. This table can be entered into Matlab and curvefitted. This leads to a quadratic relation between height and current. The height should be the input of the formula and the current should be the output, according to I=f(x). This formula has to be implemented into the feedforward controller.

The next stage is designing the braking coils with the core. The core should be of ferroxcube or another material with a minimal remanent magnetism in order not to interfere with the field of the positioning coil. A material with remanent magnetism would change the field and attract the nickelstrip to the quartztube and reducing in this way the available force. The brakingcoils should be mounted on the bottomside of the positioningcoil to achieve a good braking and holding inside the stable area. The number of turns of the brakingcoils can be 150 turns each at a length of 15 mm and two coils should be used. The mounting of the coils should be in an angle of 90° in order to pull the nickelstrip onto the quartztube and therefore increasing the friction during its fall. The coils should be mounted in such a way that the north pole of one coil is near to the south pole of the other coil (see figure VII.3).

The necessary power supplies are:

- one supply for the braking coils which can be switched on and off and that can render 2 to 3 ampères
- one voltage controllable current supply which is needed for controlling the current through the coil.

The voltage controllable current supply has to be of a good quality. This means the current should be a real direct current, no switched direct current, and the bandwith should be wide enough to enable a good tracking behaviour of the current as a function of the input voltage (around 10 kHz).

The controllercard used to control the current is an AD/DA card which has to have at least a 12 bit resolution. This to ensure that the stepsize of the current is small enough for not having any negative side effect due to a large step.

15.2. The software

The software which has to do the positioning has to take care of the following actions, in random order:

- release of the nickelstrip
- activating the brakingcoils
- activating the positioningcoil
- position the filament

During the start of a new positioncycle the software has to ensure that there is a filament ready to insert into the quartztube.

If this is so, then it has to switch the brakingcoil and the positioningcoil on and after this the filament can be released. The release of the filament has to be also controlled by the software.

Now the nickelstrip and the filament are falling and have to be braked by the brakingcoils. The software has only to measure the position and to calculate the velocity. If this velocity is small enough, less than approximately 2 cm/sec, and the filament is inside the sensorrange, then the position has to be measured at where the filament has been stopped. This position has to be translated to a current which can be calculated with the help of the earlier, in section 15.1, determined model. The current calculated has now te be set up in order to hold the filament on its place when the brakingcoils have been switched off. After this current has been set up the brakingcoils can be turned off again.

Before the controller can take over the position has to be measured, then the setpoint and procesvalue have to made equal to this value after which all the errors are set to zero and the controller can take over. This last step has to be done to start the controller from a steady state and to assure that it won't take any sudden unnecessary actions. These could cause the system to respond in an damped oscillation.

During the movement of the nickelstrip a statical value of the current can be calculated from the model. The PID controller then has to take care of reducing the dynamical error.

The tuning of the controller can be done by trial and error. This is a well suited manner because the proces dynamics is still non linear.

If the controller has reached a final state it has to give a signal which starts the melting at the point which is the most far away from the positioningcoil. This to ensure the coil won't be heated to much and unnecessarily.

After the first closing of the tube has been done the positioningcoil has to be switched off and a signal has to be generated which removes the tube. This can be done because due to the first closing of the quartztube a further positioning doesn't matter anymore.

This ends a cycle and a next one can be started.

The time flow of the program looks like:

T < 0 : wait until a filament is ready to be inserted into the quartztube

T = 0 : insert the filament and activate the brake and positioning coils

T = 0+ : measure velocity and wait until velocity is smaller than 2 cm/sec. and the filament is inside the sensor range

T = 0++ : measure position and excite the coil with the according current which has been calculated using the model, turn then the brake coils off, now measure the height and reset the error and the controller output to zero

T > 0++ : set the setpoint to the wanted value and let the controller take over the positioning

16. The horizontal set-up

Other applications could be almost everything that has to be contactfree and has the possibility of a magnetical attraction. This could be the positioning of a laserhead upto the horizontal positioning.

Horizontal positioning could be done as shown in figure 16.1. The current through each coil generates a force on the strips. The resulting force is therefore depending on the difference between the two currents. For this system it also counts that the working area is only one half of the coil. For the left coil this is the left half and for the right coil this is the right half. If the strip would move into the wrong direction the force of the other coil will increase and pull the nickelstrip back into its previous position. In this arrangement however one should pay attention to the pulling of each strip onto the filament. If the forces are to large, which can happen at à small resulting force, the filament can be distorted.

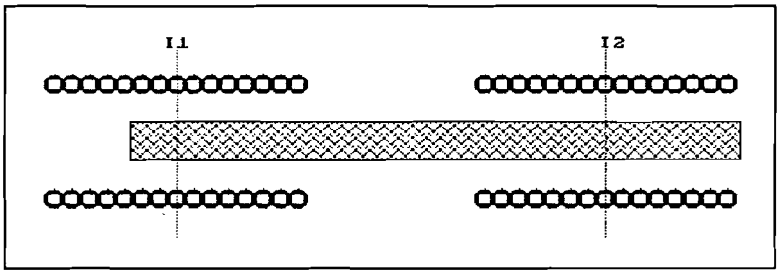


figure 16.1 : horizontal movement

There are two possibilities in which this situation can be arranged. The first is, as shown in figure 16.1, using one nickelstrip and at each end a positioning coil. But the second possibility is using two nickelstrips, one at each end of the filament, and position with two coils at those ends. The advantage of the second system is that the distance between the two coils is larger and therefore larger coils can be used. However it isn't allways possible to do this, for example the D1 doesn't have this possibility because it exists of two separate pieces (a nickelstrip, a piece of conductor, a molybdenumstrip and an electrode on each side). In this situation a configuration according to the second method isn't possible at all. In both systems the fact is being used that the field of the two coils won't interfere with eachother (see chapter 9). The maximum range in which can be controlled is the length of the strip minus the distance between the two middle points of the coils (see figure 16.1). Furthermore the ends of the strip may not pass the middle of the coil. This is because it ensures that the two coils show the same response for both the coils.

Increasing the current I_1 will result in a movement in the left direction and increasing the current I_2 results in a movement toward the right. Because only the resulting force is being used the current in the other coil can be kept zero which makes only a small current be needed in the working coil. However the other coil can be used to brake after a movement by increasing the current through the coil, the resulting force will decrease and even change direction. If the direction has changed the resulting force will brake the nickel-strip. This mechanism can be used to decrease the positioning time even further.

If, however, both coils will be activated a better and more linear transfer could be achieved.

The advantage of this type of system is that the only force working on it during the movement is the friction. This means that only a small force is needed to move the filament. Therefore in a steady-state, or when the filament has been positioned, no current is needed and therefore less energy will be used during a positioning cycle.

Though these systems haven't been tested with an controller some test have been done using the two coils. This showed that this could be a good alternative to the vertical positioning system and could be examined also.

A disadvantage of the horizontal set-up is the friction. The friction will be of a greater importance than in the vertical set-up because gravity force will now work against the system. It will now work as a friction increasing force. Furthermore this friction will be very non-linear.

Conclusions

In this report it became clear that a contactfree positioning is possible with a high speed and a high accuracy. The speed achieved is 0.4 seconds per positioning with an accuracy of 20 μm, including 0.2 seconds for dropping and braking the filament. In this vertical set-up the positioning accuracy is mainly determined by the sensor. The use of an improved sensor would improve the accuracy even further. The accuracy could also be improved by a more detailed analysis of the actuator, this would mean solving non-linear differential equations. The speed can be increased by using another method of injecting the filament into the quartztube, this could be done by using an extra force generated by air pressure (blowing the filament into the tube) or a magnetical field (and accelerating thus the filament into the tube).

A comparison teaches that this system can be competitive with the mechanical systems with regard to the price, speed and accuracy. Another advantage is the possibility of moving the filament in both directions. The mechanical system can only move the filament in one direction which means that an overshoot results in a loss of a product. The yield of the productionline will therefore increase while using this contactless positioning system.

From the vertical set-up, studied in this report, it showed that a horizontal set-up could be achieved without any substantial differences or problems except the friction.

This method of positioning can also be used in other applications in which a high accuracy is wanted combined with a high speed.

It showed also that the combination of a non-linear feedforward controller and a linear (PID) controller render good results. This combination can be used for controlling non-linear systems of which a good model exists. The inverse of the model is in the non-linear feedforward controller implemented which ensures that the system has a good statical behaviour and no error if there weren't any disturbances. The controller therefore has to ensure that the dynamical error is reduced to zero and give a good tracking behaviour.

Another important issue has been the use of a lowpass filter. By implementing this after the input a better system behaviour could be achieved. In this way a badly damped system can be forced to a good dynamical behaviour. The response time has been improved while the overshoot has been erased or reduced to a minimal value for large input changes.

From the model used it can be concluded that the widely used model of a coil mostly isn't correct and the simplifications can't be made always too.

Acknowledgement

I would like to thank mr. W. Schoenmakers who offered the practical assistance during the set-up and always took time helping me finding the equipment I needed. I would also like to mention mr. N. de Jong and mr. H. Thijs from the Design Centre L.E. who helped me creating the coils I designed. Furthermore I would like to thank all the members of the AIT and other groups, who gave me useful suggestions and I haven't mentioned before.

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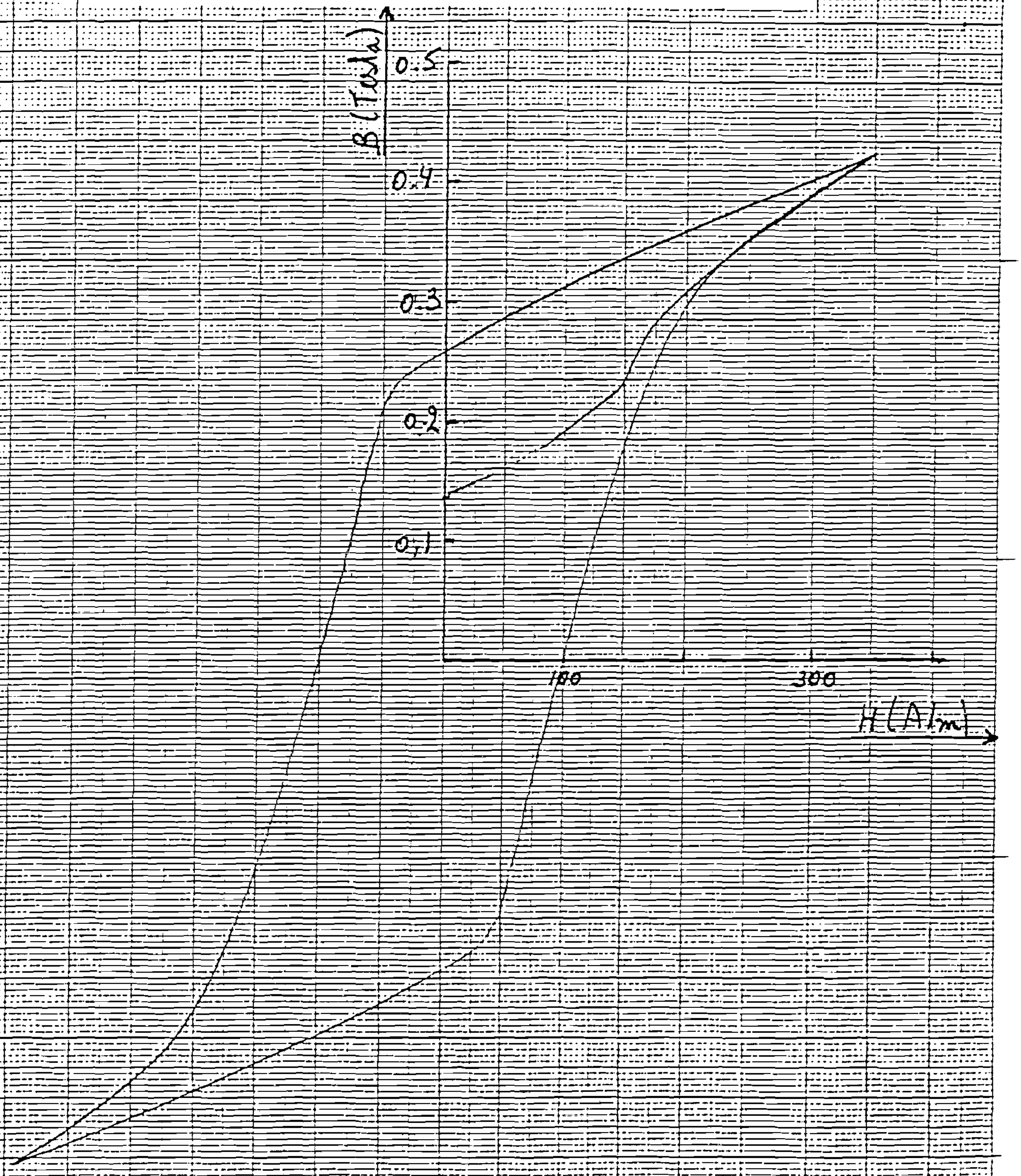
Appendix I : The hysteresis loop of nickel

Statische hysteresislus van Nikkel.
Meetunit: Strippempermeameter

Permeabiliteit umax: 1100
Hc: 153 - 143 A/m
Overige strippen Hc: 99 - 174 - 122 A/m



Appendix II: the complete derivation of the model

The formula by Biot-Savart can be used to calculate the contribution dH as a result of a current in a piece of wire with length dl which is a part of a single loop coil.

$$\overline{dH} = \frac{1}{4\pi} * \frac{I * \overline{dl} \times \overline{r}}{r^2}$$

$$\overline{dl} = \begin{pmatrix} 0 \\ 0 \\ dl_3 \end{pmatrix}$$

$$\overline{r} = \begin{pmatrix} r \cos \phi \\ - r \cos \phi \\ 0 \end{pmatrix}$$

$$\overline{dl} \times \overline{r} = \begin{pmatrix} 0 \\ 0 \\ dl_3 \end{pmatrix} x \begin{pmatrix} r \cos \phi \\ -r \sin \phi \\ 0 \end{pmatrix} = \begin{pmatrix} dl_3 \ r \sin \phi \\ dl_3 \ r \cos \phi \\ 0 \end{pmatrix}$$

$$\overline{dH} = \frac{1}{4\pi} * I \begin{pmatrix} dl_3 \ r \sin \phi \\ dl_3 \ r \cos \phi \\ 0 \end{pmatrix}$$

Because only the quantity is important this renders for dH:

$$dH = \frac{1}{4\pi} * I * dl_3 * r$$

To determine the total H in a point P on a distance r from the centre of the one turn coil, the contribution of each part dl to the total H is dH*sinϕ.

$$\overline{H} = \frac{1}{4\pi} \oint \frac{I\, d\overline{l} \times \overline{r}}{r^3} = \frac{1}{4\pi} * \frac{I * r * \sin\phi}{r^3} \oint_l d\overline{l} = \frac{I\, r \sin\phi\, 2\pi R}{r^3}\, \underline{u}_x$$

By calculating the contribution of a coil with length dx with N/l turns to the total H renders for dH:

$$dH = \frac{I * R}{2\, r^2} \sin\phi\, \frac{N}{l}\, dx$$

By using the following relations between r,R and sinϕ a simplification of dH can be made:

$$\frac{r\, d\phi}{dx} = \sin\phi$$

$$\frac{r\, d\phi}{dx} = \sin\phi$$

$$\frac{R}{r} = \sin\phi$$

$$r = \frac{dx}{d\phi} \sin\phi = \frac{R}{\sin\phi}$$

This inserting leads to:

$$dH = \frac{I\,R}{2} \sin\phi \; \frac{N}{l}\, dx \; \frac{1}{\frac{dx}{d\phi} \sin\phi \; \frac{R}{\sin\phi}}$$

Which can be rewritten to:

$$dH = \frac{I\,N}{2\,l} \sin\phi \;\; d\phi$$

The formula is now depending on an angle ϕ which runs from α to β with α and β the angles between the centreline and the ends of the coil. The total H in a point is therefore the integral from α to β:

$$H = \int_{\alpha}^{\beta} \frac{I\,N}{2l} \sin\phi \;\; d\phi = -\frac{I\,N}{2l} \cos\phi \Big|_{\alpha}^{\beta}$$

Which is:

$$H = \frac{I\,N}{2l} \left(\cos\alpha - \cos\beta \right)$$

The magnetical energy is therefore:

$$W = \frac{1}{2} * \int_V \overline{H} * \overline{B}\, dV = \frac{1}{2} * \int_V \overline{H} * \left(2*10^{-4} * \overline{H} + 0.25 \right) dV$$

In which already the relation between B and H ($B=2*10^{-4} * H + 0.25T$) has been used, while supposing that the nickelstrip has been saturated so far that the error may be neglected (which has proved to be right by the measurements).

In order to calculate the force the difference between the energylevels while moving the nickelstrip a distance Δx, has to be determined.

$$W(x) = \int_{A\,*\,\Delta x} \overline{H} * \overline{B}\, dV = \int_{\Delta x} A * \overline{H} * \overline{B}\, dx$$

$$F(x) = \frac{A*\Delta x*H(x)*B(x) - A*\Delta x*H(x\text{-}length\_strip)*B(x\text{-}length\_strip)}{\Delta x}$$

If all now known formula are entered into this equation this leads to:

$$H(x) = \frac{N * I}{2 * l}(\cos\alpha - \cos\beta) = \frac{N * I}{2 * l}\left(\frac{(l - x)}{\sqrt{R^2 + (l-x)^2}} + \frac{x}{\sqrt{R^2 + x^2}}\right)$$

$$B(x) = 2 * 10^{-4} * H + 0.25\ Tesla$$

$$F(x) = \frac{1}{2} A * \{\ H(x) * B(x) - \ldots$$

$$\ldots - H(x - length\_strip) * B(x - length\_strip)\ \}$$

$$F(x) = \frac{1}{2} A \; \{ \; 2*10^{-4} \; [\; H^2(x) \; - \; H^2(x-\mathit{length\text{-}strip}) \;] + \; . \; . \; .$$

$$. \; . \; . \; + 0.25 \; [\; H(x) \; - \; H(x-\mathit{length\_strip}) \;] \; \}$$

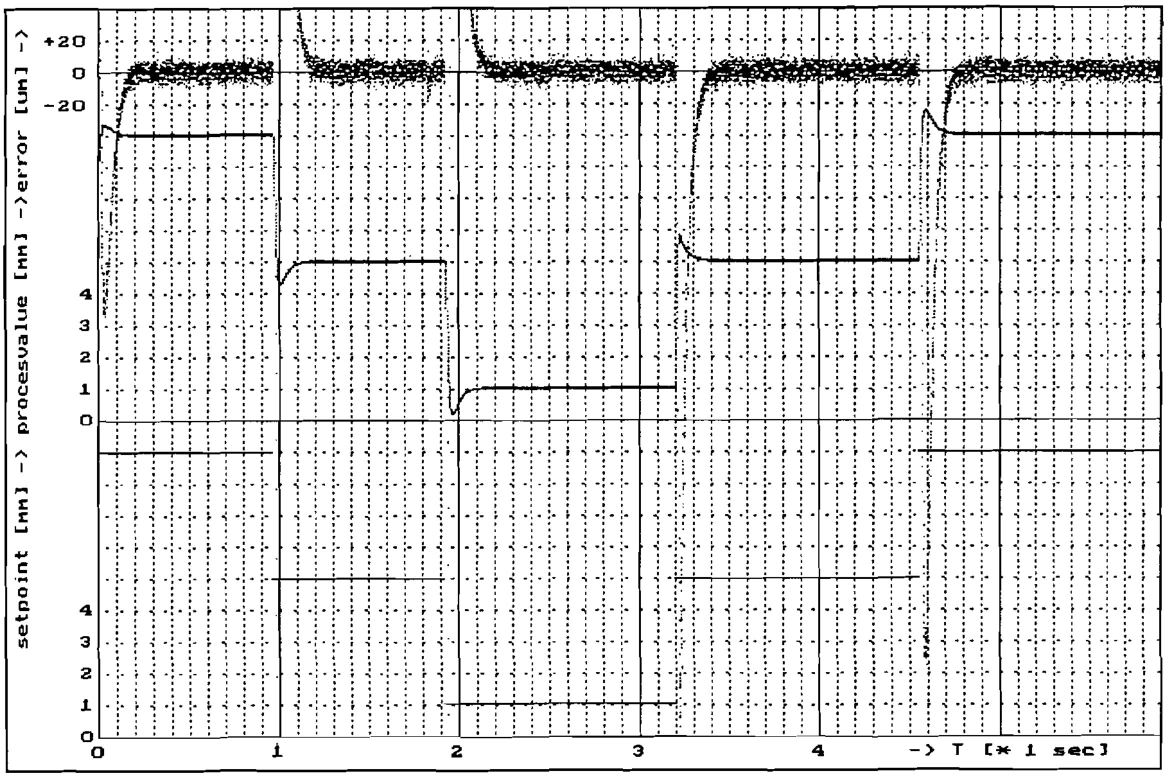
$$= \frac{1}{2} A \left\{ 2*10^{-4} \; * \left(\frac{NI}{2l} \right)^2 * \left(\left[\frac{(l-x)}{\sqrt{R^2+(l-x)^2}} + \frac{x}{\sqrt{R^2+x^2}} \right]^2 - \quad . \; . \; . \right.\right.$$

$$\left.. \; . \; . - \left[\frac{(l-x+\mathit{length\_strip})}{\sqrt{R^2+(l-x+\mathit{length\_strip})^2}} + \frac{(x-\mathit{length\_strip})}{\sqrt{R^2+(x-\mathit{length\_strip})^2}} \right]^2 \right) + \; .$$

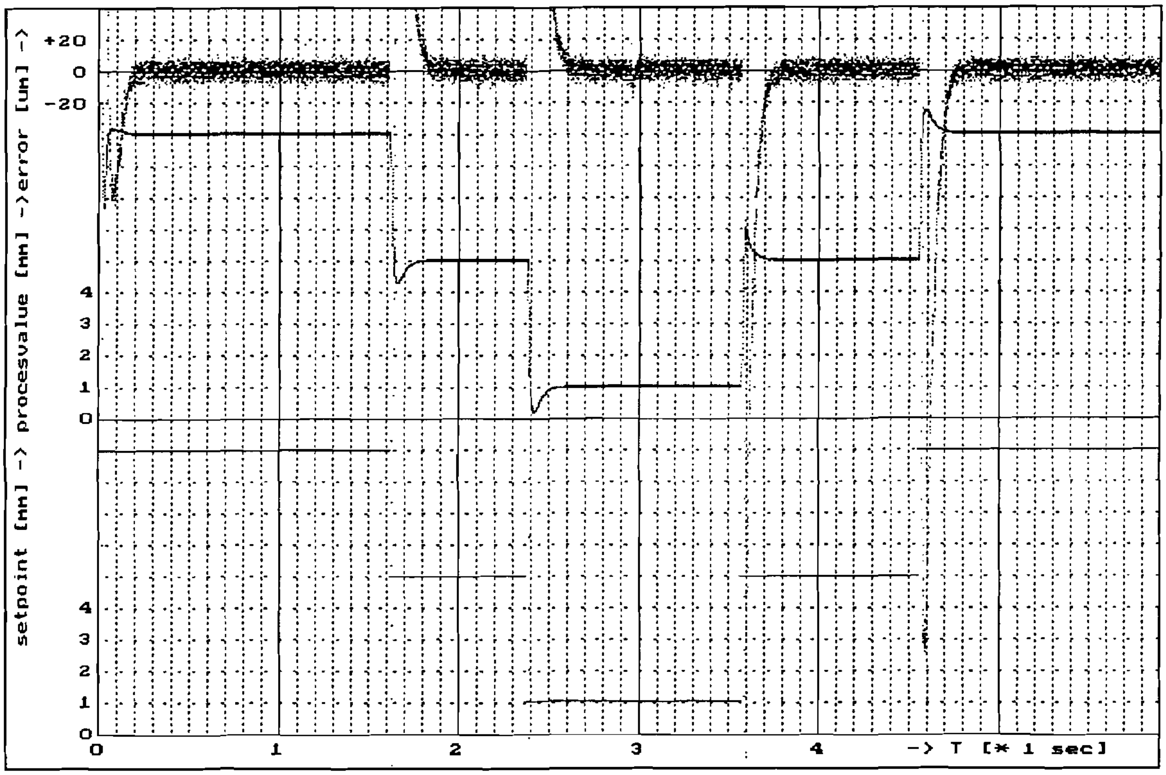
$$. \; . \; . + 0.25 \; * \; \frac{NI}{2l} \left(\left[\frac{(l-x)}{\sqrt{R^2+(l-x)^2}} + \frac{x}{\sqrt{R^2+x^2}} \right] - \; . \; . \; . \right.$$

$$\left.\left.. \; . \; . - \left[\frac{(l-x+\mathit{length\_strip})}{\sqrt{R^2+(l-x+\mathit{length\_strip})^2}} + \frac{(x-\mathit{length\_strip})}{\sqrt{R^2+(x-\mathit{length\_strip})^2}} \right] \right) \right\}$$

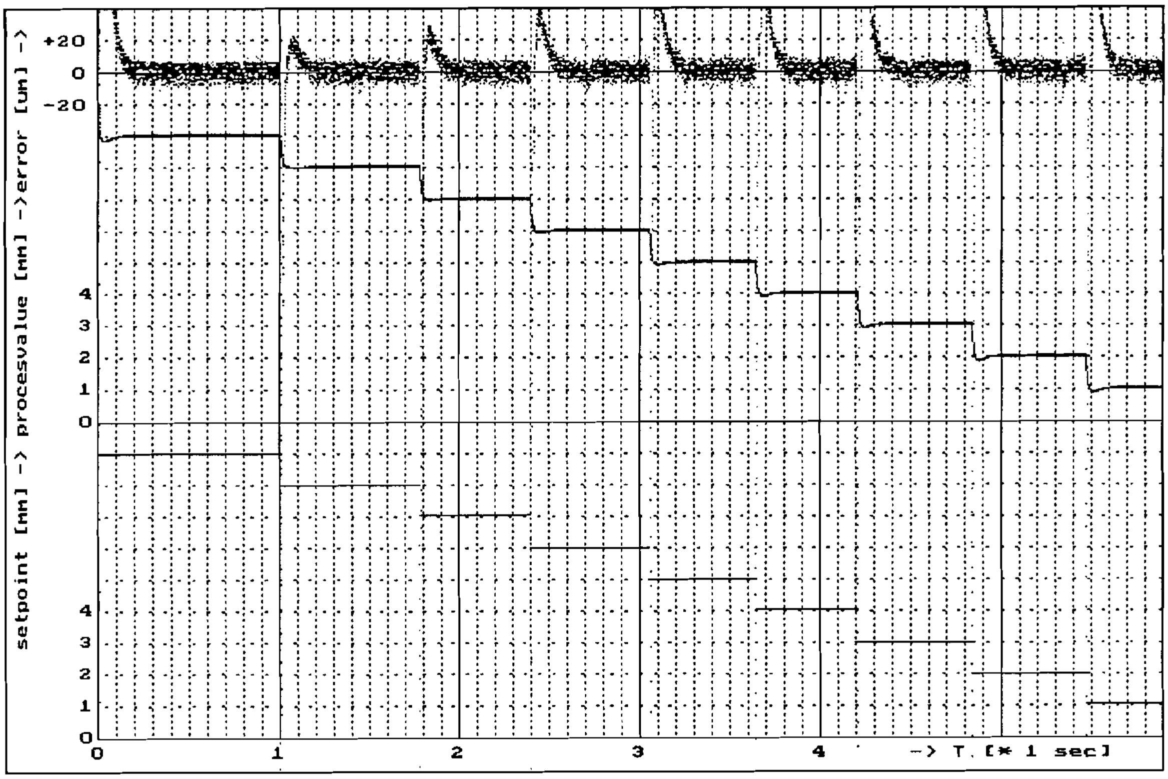
Appendix III : some measurement results of the controller without the low pass filter



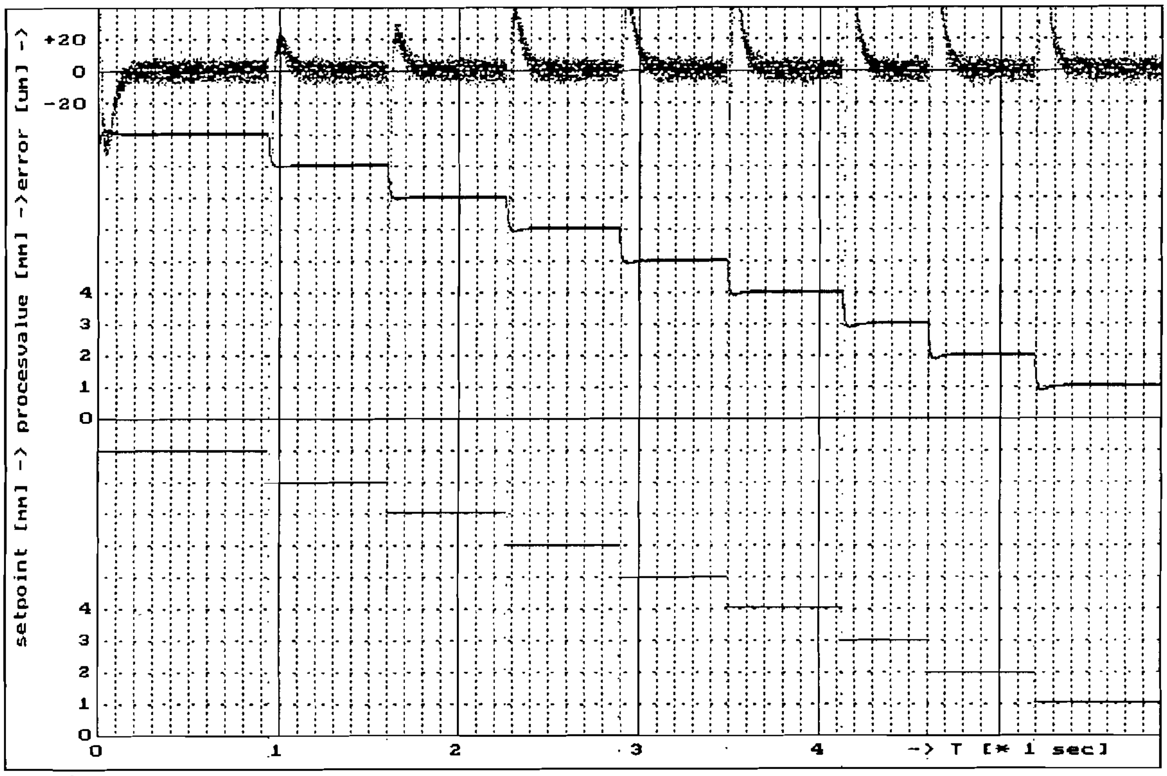
strip I



strip II



strip I



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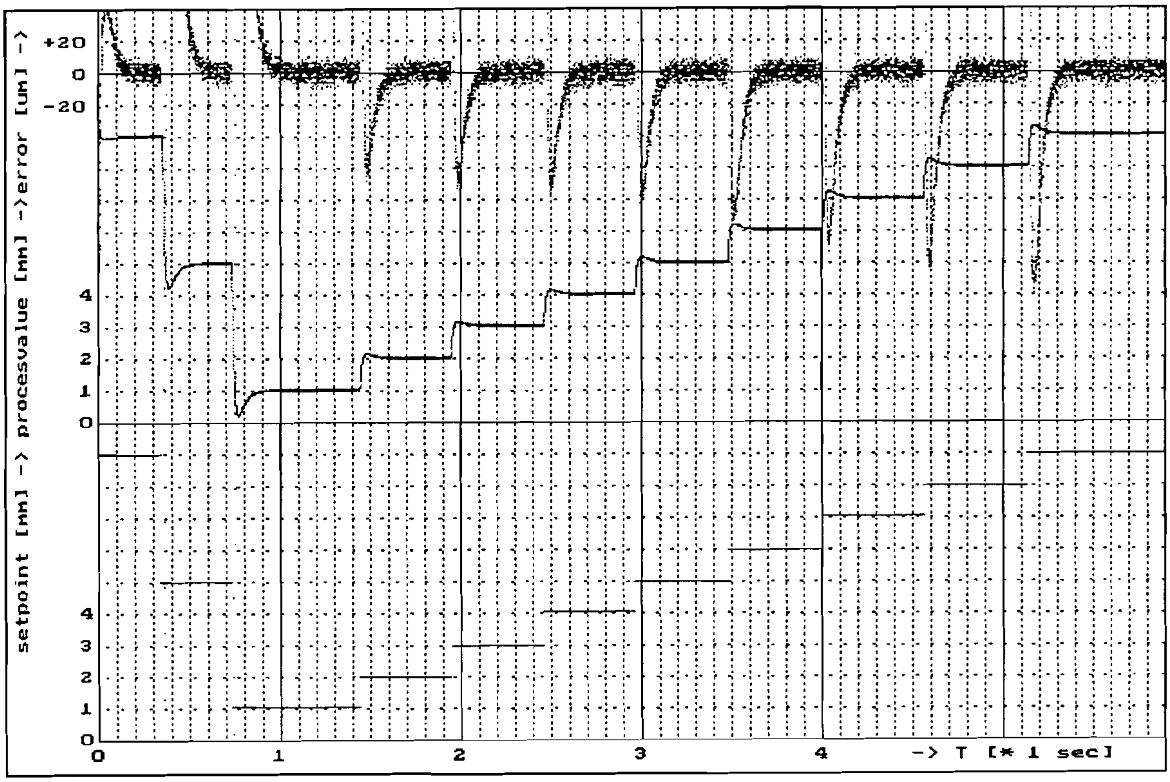
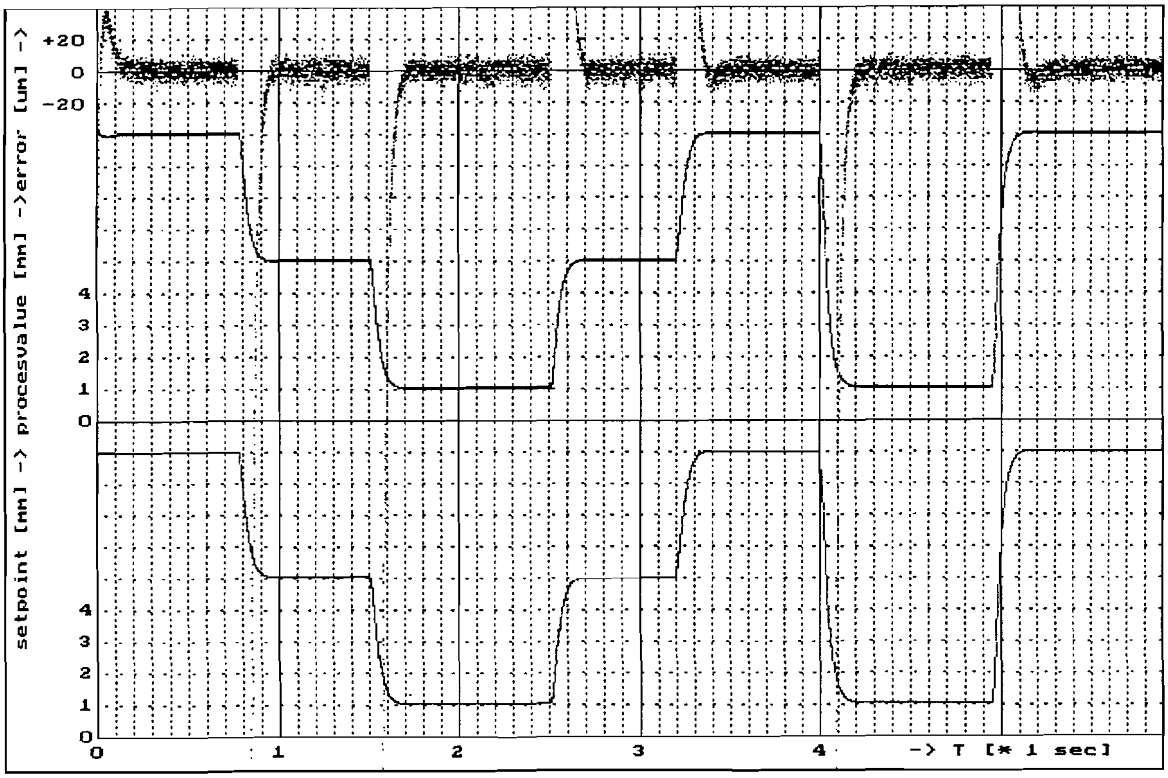


strip I

strip II

Appendix IV : some measurement results of the controller including the low pass filter



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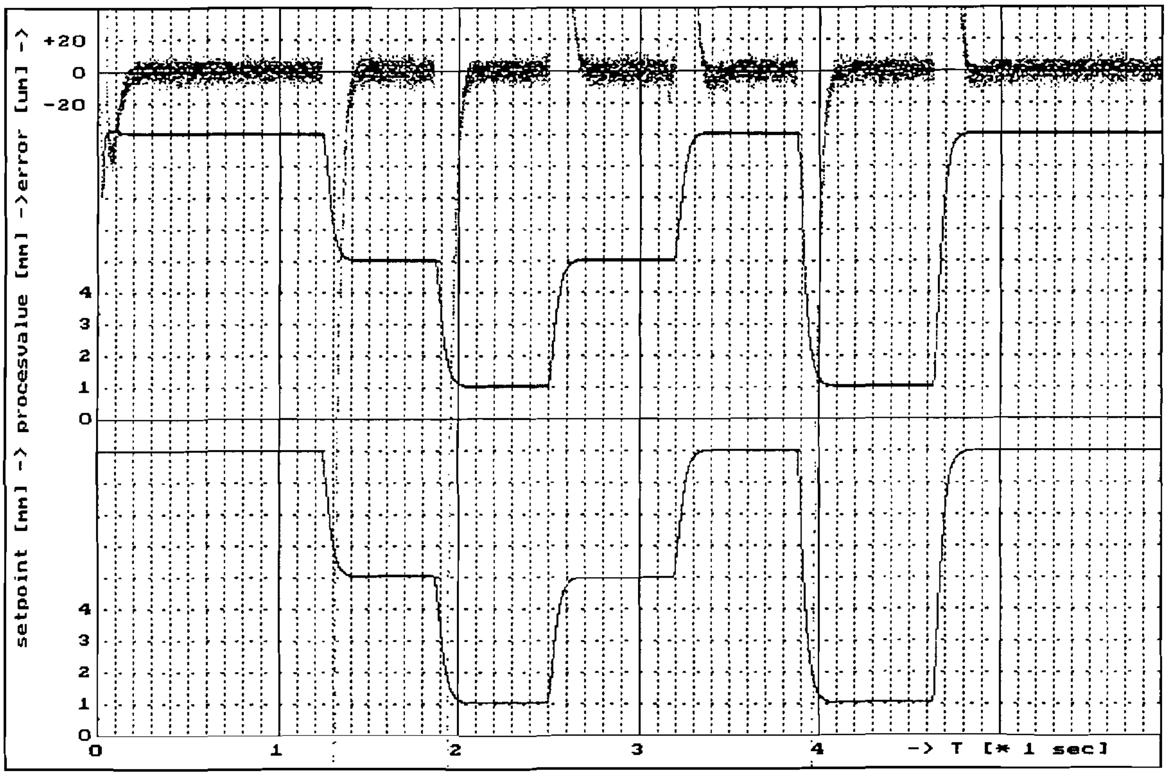
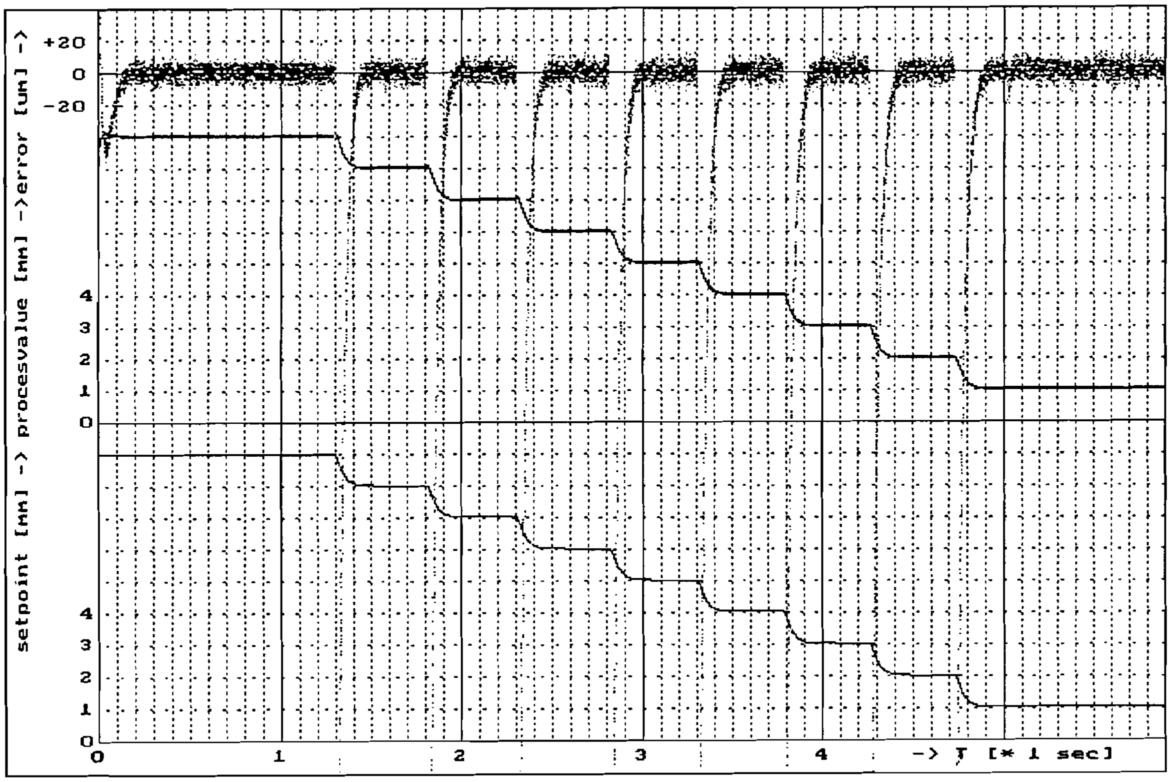
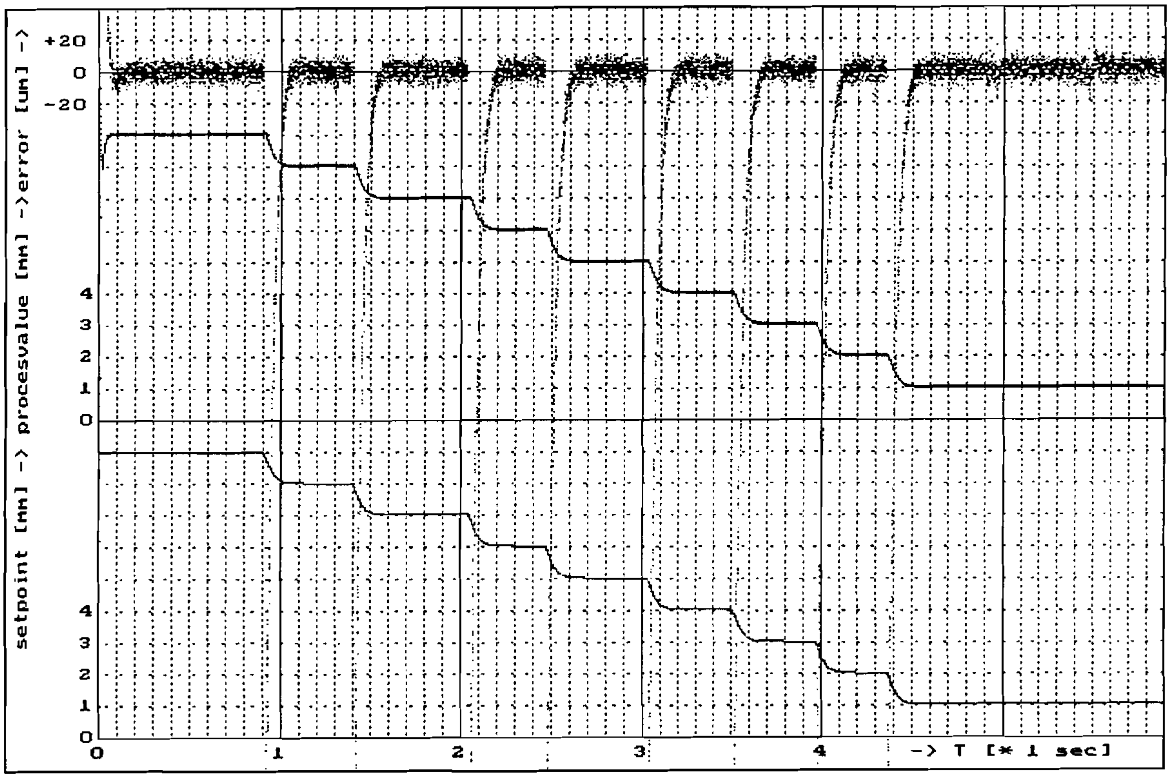


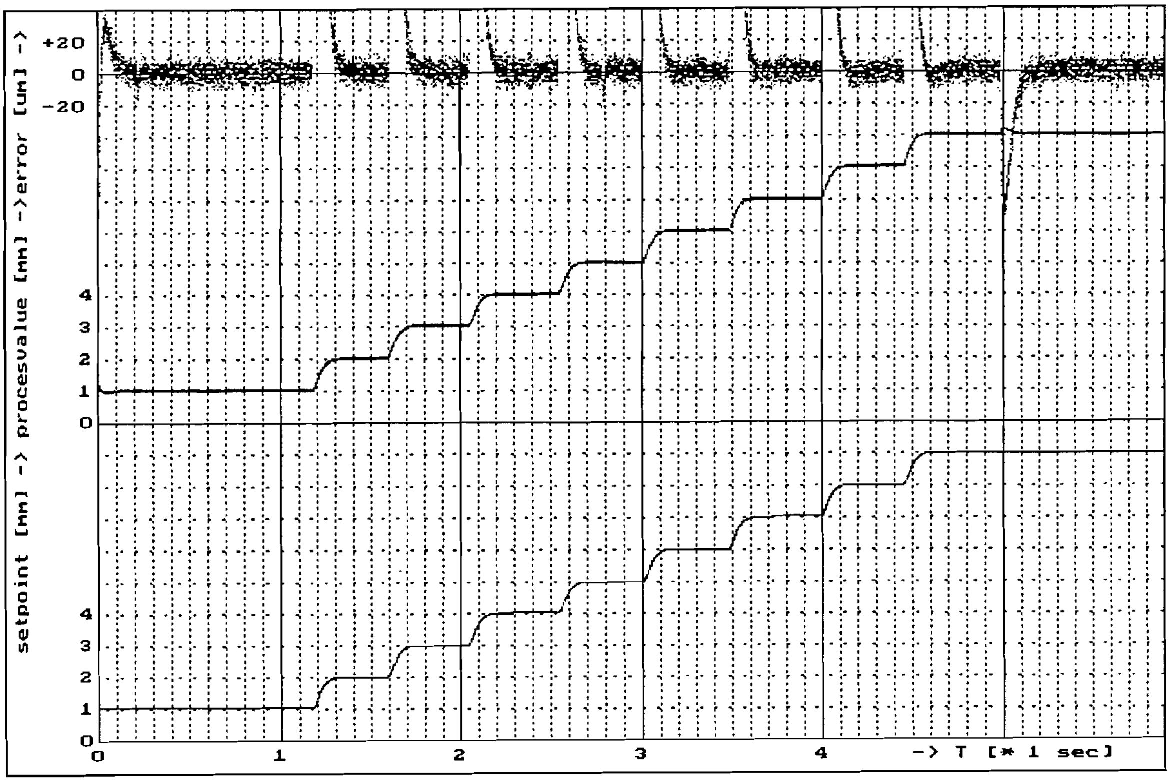
strip II



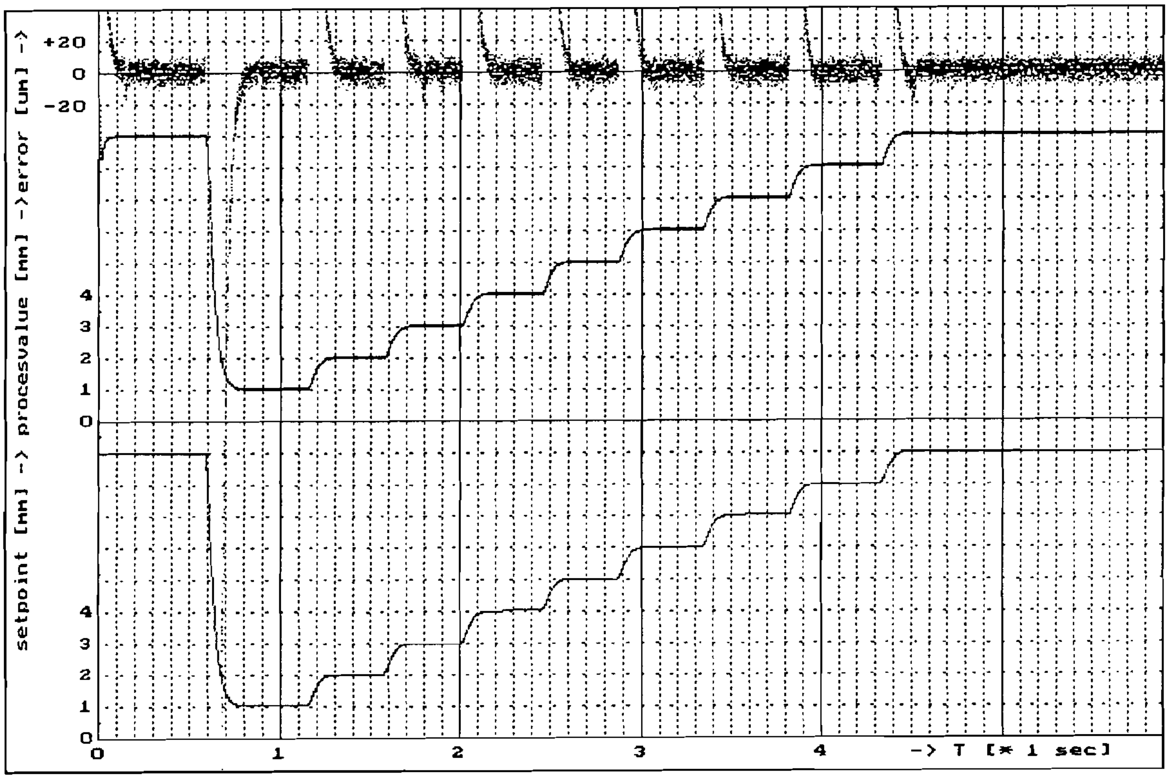
strip I



strip II

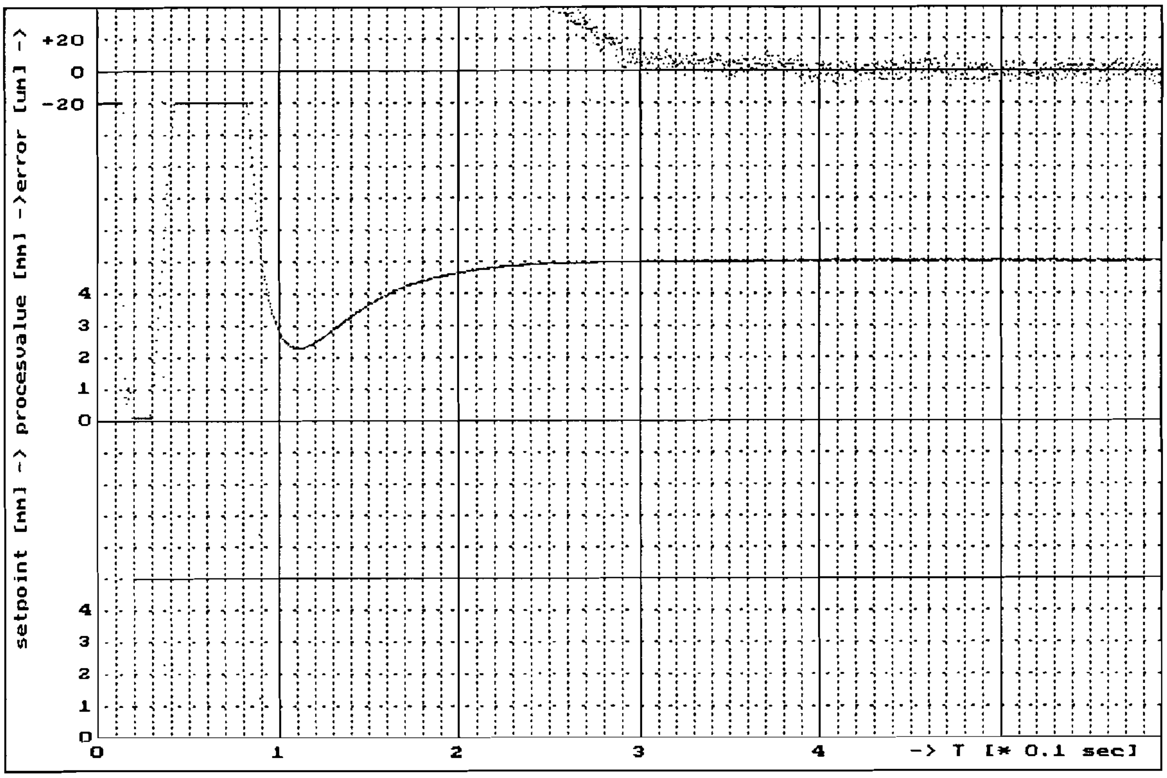


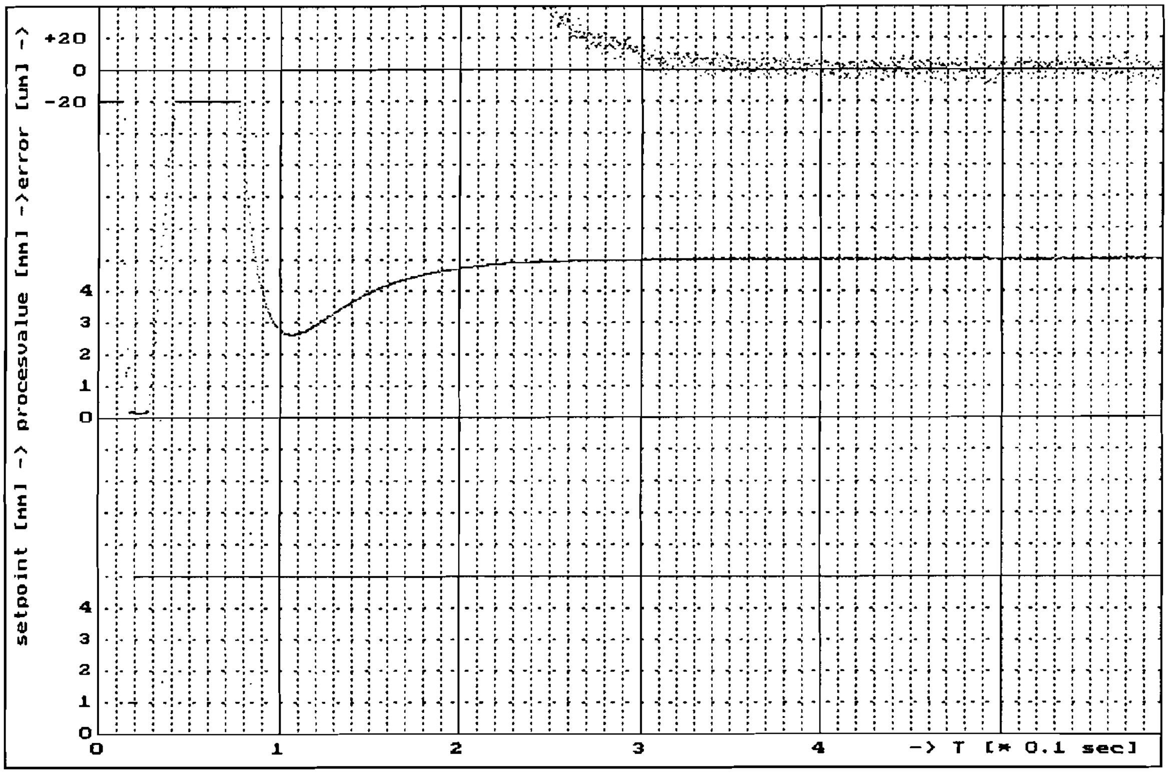
strip I



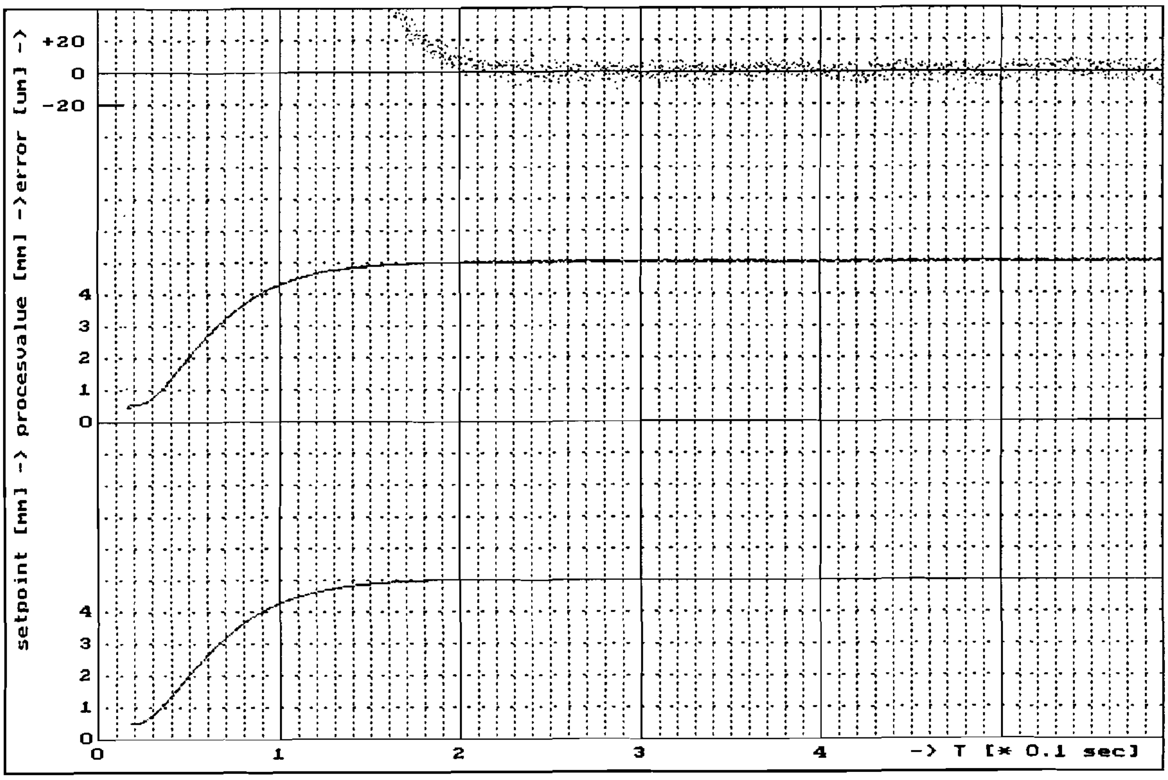
strip II

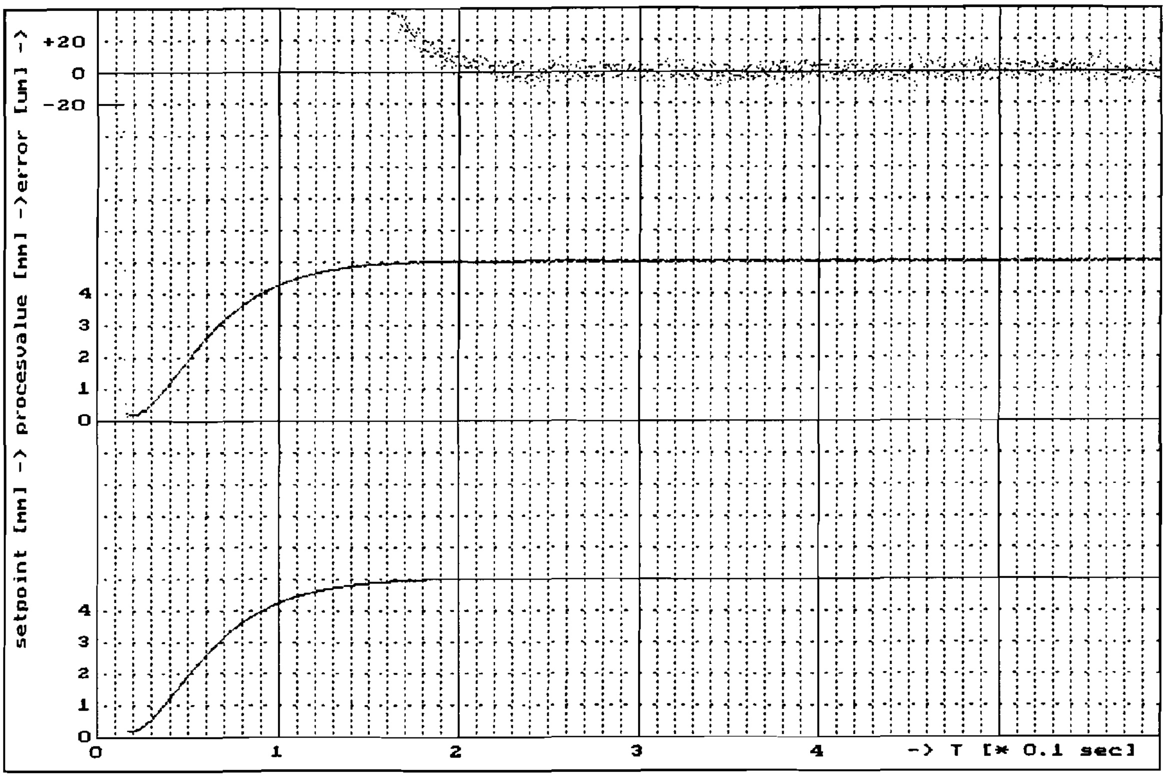
Appendix V : braking and positioning results without using the low pass filter

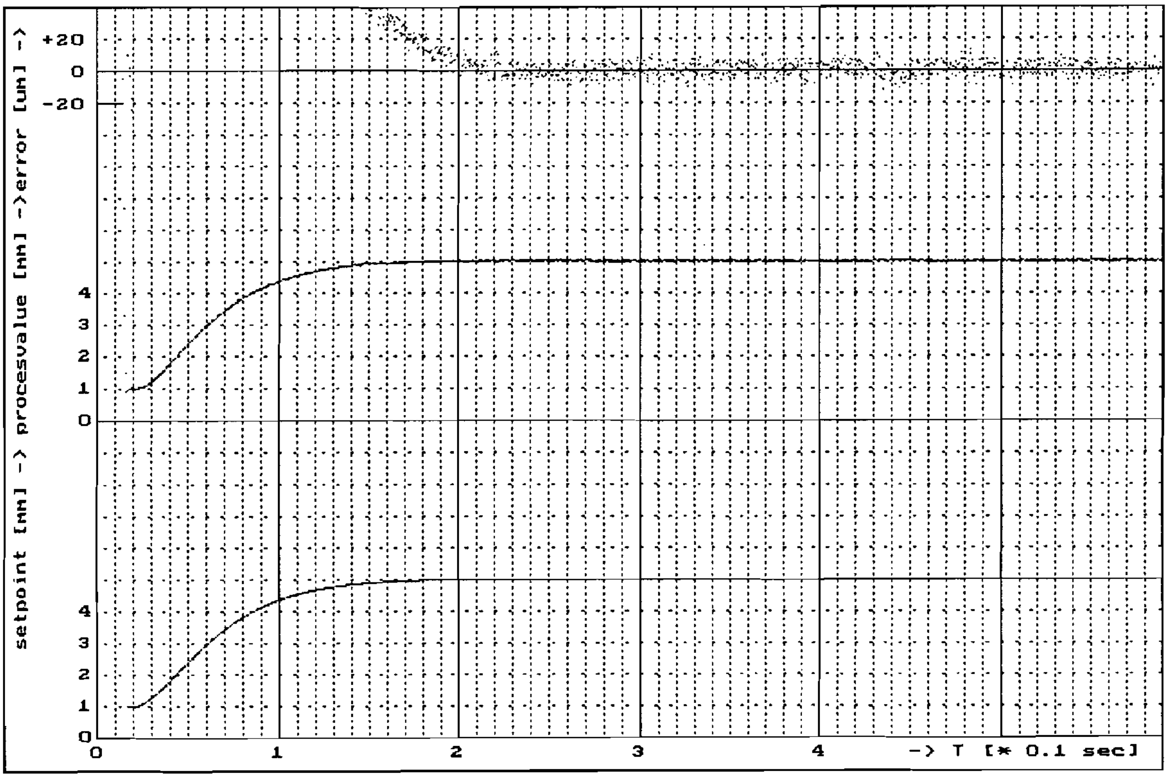




Appendix VI : Braking and positioning results using the low pass filter






setpoint [mm] -> procesvalue [mm] ->error [um] ->
+20
0
-20
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2
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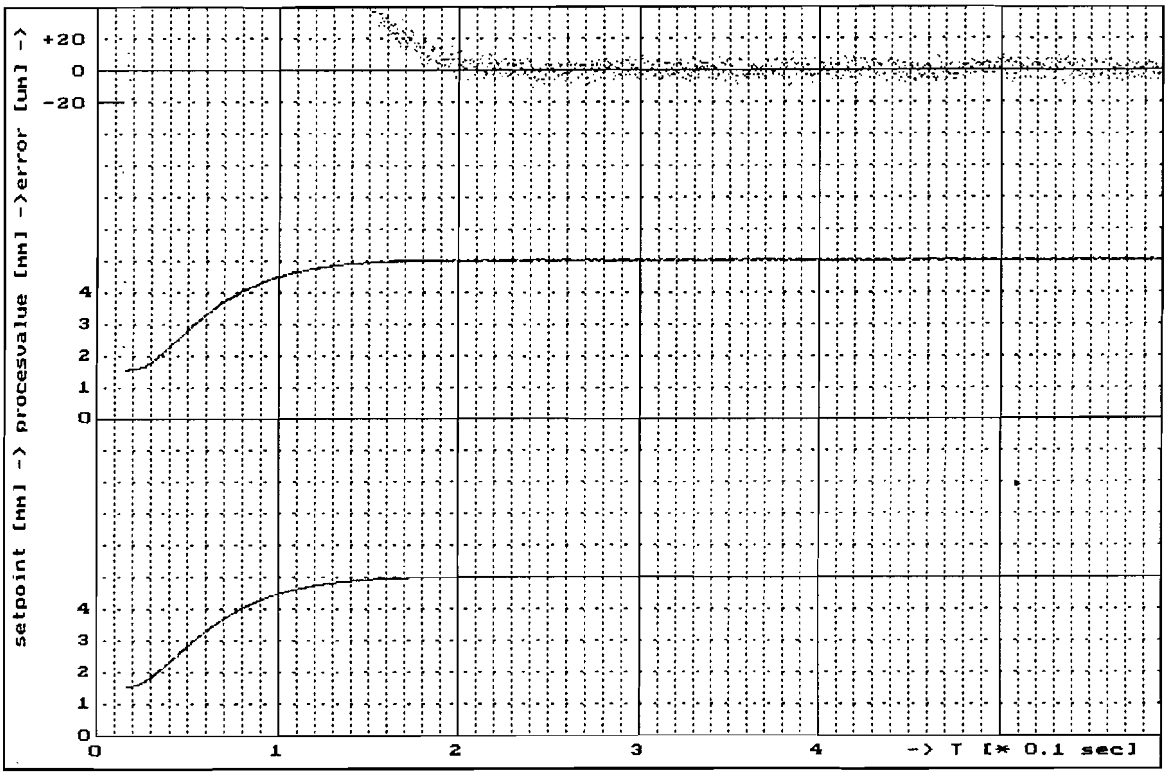
4
-> T [* 0.1 sec]


setpoint [mm] -> procesvalue [mm] ->error [um] ->
+20
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-> T [* 0.1 sec]

Appendix VII : figures and dimensions of the mechanical parts

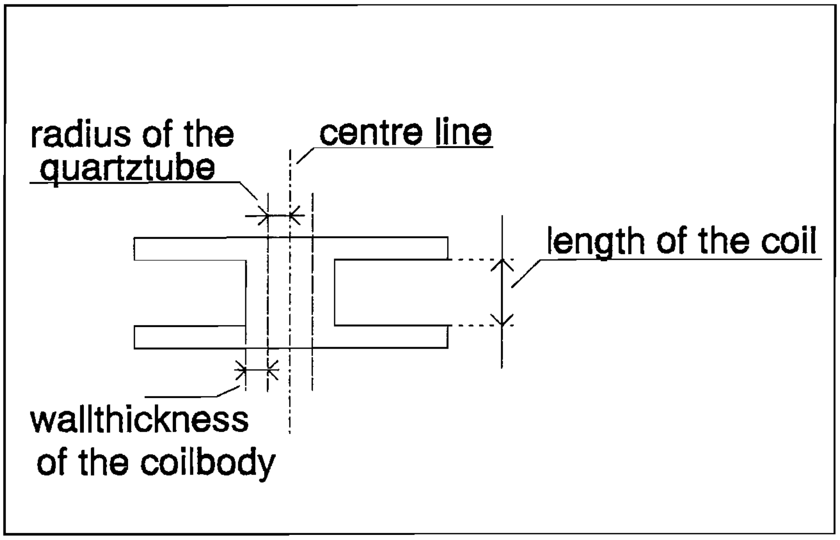

figure vii.1

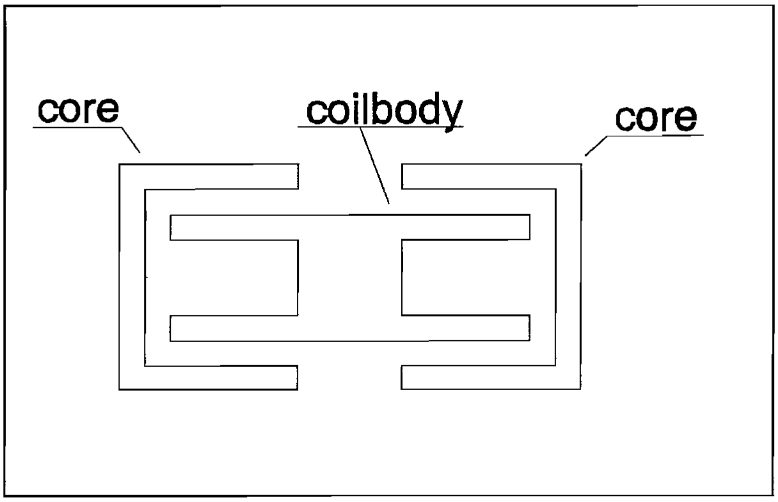

figure vii.2

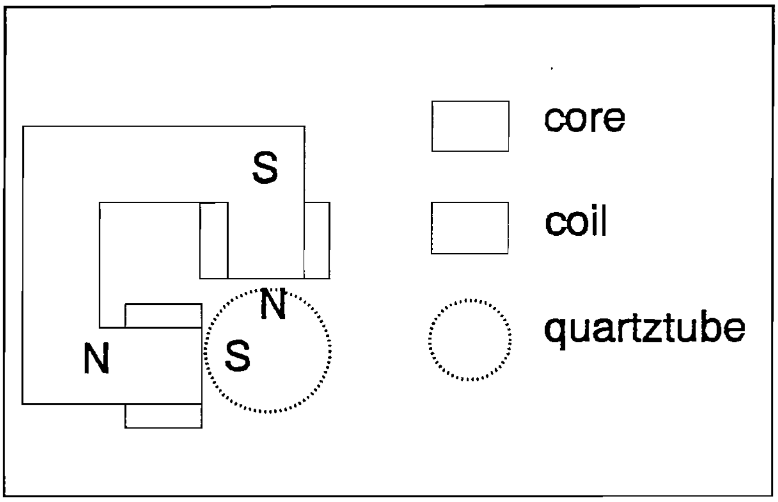

figure vii.3

Appendix VIII : the used equipment

- I/O card Keithley DAS 1602
- Turbo Pascal V6.0
- Keyence laser sensor LX-130
- Kepco Bipolar Operational Power Supply / Amplifier
  BOP 20/20M
  Nat. Lab. contact: R. Brus
- three power supplies which are needed for the electro magnet (1.5 A), the laser sensor (15 V) and the brake coils (2 A)